Glacial lake outburst flood risk in the Bolivian Andes

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“Φύσις κρύπτεσθαι φιλεῖ.”
Ηράκλειτος, 544-484 π.Χ., Έλληνας προσωκρατικός φιλόσοφος

Which poetically translates to...

“Nature, clearly seeks to remain something of a mystery.”
Heraclitus, 544-484 BCE, pre-Socratic Greek philosopher

Dedicated to my father, from whom I got the passion for

Nature, Science, Philosophy, Exploration & Maps…

and to my mother, who taught me how to accomplish

even the most demanding operational tasks.

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Abstract

The Bolivian Andes have experienced sustained and widespread glacier area reduction and volume loss in recent decades. This study finds that from 1986 to 2018 glacier areas have shrunk from 529 km^2 to 281 km^2 (49 %) in the Bolivian Cordillera Oriental. Glacier melting and recession has been accompanied by the development of proglacial lakes, which can pose a glacial lake outburst flood (GLOF) risk to downstream communities. Therefore, glacier bed topographies were extracted and illustrate the potential development of 68 future lakes. Eight of these lakes possess populations downstream. A simple geometric model (MC-LCP) was used to model GLOFs from these potential future lakes, illustrating that ~1100 to ~2900 people could be affected by flooding if these lakes were to appear and to burst. The rest of this work is dedicated on the estimation of the risk from current, already existing lakes. Multi-Criteria Decision Analysis (MCDA) was used to rapidly identify potentially dangerous proglacial lakes in regions around the world without existing tailored GLOF risk assessments, where a range of proglacial lake types exist, and where field data are sparse or non-existent. After testing the robustness of the MCDA model against a number of past GLOFs, it was applied to the Bolivian Cordillera Oriental. From the 25 lakes possessing populations downstream, 3 lakes were found to pose 'medium' or 'high' risk, and required further detailed investigation. Since no attempt has yet been made to model GLOF inundation downstream from these proglacial lakes, 2m resolution DEMs were generated from stereo and tri-stereo SPOT 6/7 satellite images to drive a hydrodynamic model (HEC-RAS 5.0.3) of GLOF flow. The model was tested against field observations of a 2009 GLOF from Keara, in the Cordillera Apolobamba, and was shown to reproduce realistic flood depths and inundation. The model was then used to model GLOFs from Pelechuco lake (Cordillera Apolobamba) and Laguna Arkhata and Laguna Glaciar (Cordillera Real). In total, ~1100 to ~2200 people could be directly affected by outburst flooding.

Contents

List of figures xii

List of tables xvi

Chapter 1 - Introduction 1

1.1 Introduction 2

1.2 Scientific background and rationale for this study 2

1.3 Aims 5

1.4 Objectives and thesis structure 5

Chapter 2 - Literature Review 9

2.1 Causes and consequences of glacier change 10

2.1.1 Climate change and global mountain glacier shrinkage 10

2.1.2 Characteristics of tropical Andean glaciers 13

2.1.3 Bolivia 15

2.2 Proglacial lake development: location, formation and evolution 19

2.3 Definition, causes, and consequences of GLOFs 24

2.3.1 Incidences of GLOFs around the globe 24

2.3.2 Triggering causes and consequences of GLOFs according to dam types 25

2.4 Definitions, perceptions and concepts of risk 30

2.4.1 Disaster risk management: different approaches 30

2.4.2 A new definition of risk 32

Chapter 3 - Glacier change, proglacial lake development and future GLOF risk in Bolivia **34**

3.1 Introduction **35**

3.2 Methods **36**

3.2.1 Mapping glacier area and proglacial lake changes in the Bolivian Cordillera Oriental (2014 – 2018) 36

3.2.2 Range divide and altitudinal controls on glacier change 38

3.2.3 Modelling ice-thickness for potential future lake development (2018 - onwards) 43

3.2.4 Qualitative hazard assessment of potential future lakes 47

3.2.5 Monte Carlo Least Cost Path (MC-LCP) model 48

3.2.6 Population, infrastructure data and potential impacts 48

3.3 Results **49**

3.3.1 Glacier area changes and proglacial lake development in the Bolivian Andes (2014 - 2018) 49

3.3.2 Future lake development (2018 - onwards) 60

3.3.3 Qualitative hazard assessment of potential future lakes 62

3.3.4 Potential GLOF impact assessment 68

3.3.5 Preliminary risk assessment of potential future lakes in the Bolivian Cordillera Oriental 73

3.4 Discussion **75**

3.4.1 Glacier shrinkage and impacts on water resources in the Bolivian Cordillera Oriental 75

3.4.2 Proglacial lake development in the Bolivian Cordillera Oriental 78

3.4.3 Future GLOF risk in the Bolivian Cordillera Oriental 79

3.5 Conclusion **80**

Chapter 4 - Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes 82

4.1 Introduction 83

4.2 Methodology 86

4.2.1 Background to setting an MCDA problem 86

4.2.2 The description problem: determining the criteria that define GLOF risk 87

4.2.3 The sorting problem: Past GLOF events and potentially dangerous lakes 93

4.2.4 Choice of lakes for testing 94

4.2.5 SMAA-TRI software 95

4.2.6 Setting risk thresholds and codes for evaluating individual criteria 96

4.2.7 Sensitivity analysis 98

4.3 Results 99

4.3.1 Assessing GLOF risk: an application to past and potential future events 99

4.3.2 Lambda cutting level sensitivity analysis 100

4.3.3 Criteria thresholds sensitivity analysis 102

4.3.4 Application to a data-scarce region: the Bolivian Andes 104

4.4 Discussion 105

4.4.1 Comparisons with existing GLOF hazard and risk assessments 105

4.4.2 Comparisons of model results with GLOF-generating lakes 106

4.4.3 Potentially dangerous glacial lakes of the Bolivian Andes 107

4.4.4 MCDA model sensitivity 108

4.4.5 The use of MCDA in GLOF risk assessments 110

4.5 Conclusion 112

Chapter 5 - Modelling glacial lake outburst flood impacts in the Bolivian Andes 114

5.1 Introduction 115

5.2 Geographical setting and methods 115

5.1.1 Geographical setting 115

5.1.2 Topographic data acquisition 119

5.1.3 Estimating lake volume 121

5.1.4 Estimating peak discharge 122

5.1.5 Dam breach hydrograph and modelling parameters 123

5.1.6 Hydrodynamic modelling of GLOFs 125

5.1.7 Population and infrastructure data 127

5.3 Results 129

5.1.8 Modelling the 2009 Keara GLOF 129

5.1.9 Potential GLOF impacts from three dangerous lakes 130

5.4 Discussion 134

5.1.10 Modelling approach 134

5.1.11 GLOF impacts and risk management 137

5.5 Conclusion 139

Chapter 6 - Conclusions and future research **140**

6.1 Conclusions **141**

6.2 Future research **145**

6.2.1 Glacier demise and water scarcity 145

6.2.2 Ice thickness and climatic data monitoring 146

6.2.3 Proglacial lake development and GLOF hazard and risk assessments 146

6.2.4 Paraglacial processes 147

6.2.5 Debris-covered glaciers and rock glaciers 148

References **150**

Appendices **177**

List of figures

Fig. 1.1. Topographic map of Bolivia and current glaciated areas along the Bolivian Cordillera Oriental. Base map is the Esri World Shaded Relief map (2014). 4
Fig. 2.1. Glacier Mass Balance (Adapted from Bennett and Glasser, 2009) 11
Fig. 2.2. Response to an upward shift of the equilibrium line altitude (ELA) for three glacier types (Adapted from Vaughan et al., 2014). Accumulation zones (white), ablation zones (light blue), meltwater (dark blue). 12
Fig. 2.3. Example of a bedrock-dammed lake (Laguna Arkhata / coordinates: 19 K 624521 8172040): (A) Evolution of the lake in longitudinal view, (B) Google earth image (2016), (C) Photo of the lake (tantan tanuki) 20
Fig. 2.4. Example of a moraine-dammed lake (Pelechuco / coordinates: 19 L 481205 8365591): (A) Evolution of the lake in longitudinal view, (B) Google earth image (2016), (C) Photo of the lake (SJ. Cook, 2015) 21
Fig. 2.5. Example of an ice-dammed lake (Mendenhall Lake in Alaska / coordinates: 8 V 525112 6475896): (A) Evolution of the lake in plan view, (B) Google earth image (2016), (C) Photo of the lake (U.S. Geological Survey webcam) 22
Fig. 2.6. Example of a landslide-dammed lake (Loch Nagar in New Zealand / coordinates: 59 G 309609 5059766): (A) Evolution of the lake in plan view, (B) Google earth image showing approximate landslide limits (2016), (C) Photo of the lake showing approximate landslide limits (nickorama) 23
Fig. 2.7. Lake 513 GLOF, Peru (coordinates: 18L 219791 8980650): (A) lake and stream before the incident (2002), (B) lake and stream after the incident (2013). 26
Fig. 2.8. Palcacocha Lake GLOF, Peru (coordinates: 18 L 238608 8960350): (A) glacier before recession and lake creation, (B) glacier recession and moraine-dammed lake creation, (C) collapse of an unstable part of the slope leaping over or destroying the dam, (D) Photo before the 1941 event (German and Austrian Alpine Club DuOAV), (E) Photo 71 years after the event (Sergiu Jiduc). 27
Fig. 2.9. Keara Lake GLOF, Bolivia (coordinates: 19 L 481932 8377262): (A) lake and infiltration through the ice-dam, (B) increased infiltration leading to calving and icefalls, (C) sudden failure of the ice dam 29
Fig. 2.10. (A) Incision and boulder transport due to the GLOF, (B) disaster aftermath (Martín Apaza Ticona) 29

Fig. 2.11 Disaster Risk Management (Adapted from Wood-USGS, 2011) 31
Fig. 2.12. The disaster management cycle (Moe and Pathranarakul, 2007; Janssen et al., 2010) 31
Fig. 3.1. Map illustrating the range divide in the Bolivian Cordillera Oriental. 39
Fig. 3.2. Maps illustrating the altitude divisions on glaciers of the Cordillera Oriental between 1986 and 2018. Top: Cordillera Apolobamba, Middle: Cordillera Real, Bottom: Cordillera Tres Cruces. 42
Fig. 3.3. Left: GlabTop method applied on Zongo glacier with the 2010 glacier outline. Right: GPR values obtained in 2010 by Réveillet et al. (2015). Right figure credit: Réveillet et al. (2015) 44
Fig. 3.4. Comparison of results from steps 1, 2 and 3 with the 2018 glacier outlines in a selected area in the Cordillera Tres Cruces. Mapping method following Frey et al. (2010), Colonia et al. (2017) and Drenkhan et al. (2018). 46
Fig. 3.5. Glaciated area changes in the three mountain ranges between 1986 and 2018. For mountain range locations in Bolivia see Fig. 1.1. For visibility purposes, only 1986 and 2018 areas are present on these maps. Base map is the Esri World Shaded Relief map (2014). 50
Fig. 3.6. Glacier area (km^2) and areal change (superimposed numbers on the graph in %) across the Bolivian Cordillera Oriental. Error bars are determined using Eq. (1) and represent an uncertainty of ± 10 %. 53
Fig. 3.7. Glacier area (km^2) between the west-facing and the east-facing basins across the Bolivian Cordillera Oriental... 56
Fig. 3.8. Glacier area (km^2) between different altitudes (<5000 m asl.; 5000-5500 m asl.; >5500 m asl.) across the Bolivian Cordillera Oriental.. 59
Fig. 3.9. Examples of overdeepenings (red) identified by GlabTop in the three Cordilleras of the Bolivian Andes. Left: Apolobamba, Centre: Real, Right: Tres Cruces. 61
Fig. 3.10. Location of subglacial overdeepenings that could form lakes when glaciers recede and which possess population downstream. 62
Fig. 3.11. Location of lakes A, B and C (blue polygons) and the communities potentially affected (red circles). 64
Fig. 3.12. Location of lakes D, E and F (blue polygons) and the communities potentially affected by future GLOFs (red circles). 65

Fig. 3.13. Location of lakes H and G (blue polygons) and the communities potentially affected by future GLOFs (red circles). 66
Fig. 3.14. GLOF impacts (from potential future lakes) on four communities in the Cordillera Apolobamba. Yellow=optimistic scenario. Red = pessimistic scenario..........68
Fig. 3.15. GLOF impacts (from potential future lakes) on three communities in the Cordillera Real. Yellow=optimistic scenario. Red = pessimistic scenario. 69
Fig. 3.16. GLOF impacts (from potential future lakes) on five communities in the Cordillera Tres Cruzes. Yellow=optimistic scenario. Red = pessimistic scenario. 70
Fig. 3.17. Matrix illustrating the level of risk from each potential future lake. Left: optimistic scenario, Right: pessimistic scenario. 74
Fig. 4.1. Flow diagram of the GLOF risk assessment procedure. Supplementary information about the final set of criteria can be found in Appendix 4.1. 90
Fig. 4.2. Flow diagram for the Multi-Criteria Decision Analysis (MCDA) method. Step 1: the user downloads all data and software needed for the evaluation; Step 2: the proglacial lake dataset to be analysed is extracted; Step 3: introducing the parameters to the software and computation of the result; Step 4: Sensitivity Analysis 94
Fig. 5.1. Location of glaciers and potentially dangerous glacial lakes in the Bolivian Andes, as well as the 2009 Keara GLOF event. The risk of each glacial lake identified by Cook et al. (2016) was assessed by Kougkoulos et al. (2018) using the MCDA methodology; three lakes were graded as ‘medium’ (orange) and ‘high’ risk (red), and form the focus of this study 116
Fig. 5.2. Example breach hydrograph for Pelechuco lake illustrating all three scenarios for a potential GLOF (optimistic, intermediate and pessimistic). The same hydrograph shapes are used for all three lakes...125
Fig. 5.3. Photos illustrating typical brick structures with roofs made from corrugated steel sheets. Pelechuco (A and B), Sorata (C). Photo credit: Dirk Hoffmann 128
Fig. 5.4. Numerical simulation of the Keara November 2009 GLOF event. Zone A shows 4-6 m flow depths corresponding a ~5 m deep incision through proglacial till illustrated in the field photo. Zone B replicates flood inundation areal extent around farm buildings and walls with favourable comparison to the accompanying field photo (note that the photograph is taken from a different orientation to the model run image). Zone C illustrates impacts on the Keara community (a focused view is presented in Fig.

5.5). The photos were taken in the field on November 3rd 2009, only hours after the event, by Martin Apaza Ticona, and used with his permission. 129
Fig. 5.5. Focused view of impacts on the Keara community. Photo credit: Martin Apaza Ticona. 130
Fig. 5.6. Potential impacts for each modelled scenario for a GLOF (>2 m flood depth) originating from Pelechuco lake. ASTER GDEM (30 m resolution) was used for Agua Blanca, because gaps created by shading on the 2 m SPOT extracted DEM made evaluation impossible. For Pelechuco, the 2 m DEM was used. 131
Fig. 5.7. Potential impacts for each modelled scenario for a GLOF (>2 m flood depth) originating from Laguna Glaciar. 133
Fig. 5.8. Potential impacts for each modelled scenario for a GLOF (>2 m flood depth) originating from Laguna Arkhata. 134
Fig. 5.9. Potentially affected population numbers per community and per modelled scenario. Left (optimistic), Centre (intermediate), Right (pessimistic).........................137

List of tables

Table 2.1. Summary table of ice-dammed lakes by triggering mechanism and cause of drainage (Adapted from Tweed and Russell, 1999)..28

Table 3.1. Summary of Landsat scenes used in this study...36

Table 3.3. Hazard criteria selected for the potential future lake evaluation (from Kougkoulos et al., 2018a)..47

Table 3.4. Evaluation of hazard criteria per potential future lake................................67

Table 3.5. Estimated number of buildings and population affected per community and per scenario (optimistic and pessimistic) in the event of hypothetical future floods....72

Table 3.6. Qualitative evaluation of lake hazard and community impact parameters for both scenarios (optimistic scenario and pessimistic scenario) in the event of hypothetical future floods. 74

Table 4.1. Review of criteria assessed in previous studies. Top section outlines the process followed to accept or reject a criterion. Middle section shows the results. Bottom section illustrates the literature used. The accepted criteria in the middle section are illustrated in Fig. 4.1. 84

Table 4.2. Criteria units, evaluation methods, main risk thresholds and sensitivity analysis thresholds. Details on criteria threshold determination can be found in Appendix 4.1. 90

Table 4.3. Potentially dangerous lakes and selected GLOF events derived from previous studies. Risk level derived from the MCDA method. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific risk class. Low risk = Green, Medium risk = Orange, High risk = Red. 93

Table 4.4. Sensitivity analysis based on alteration of the lambda cutting level. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific risk class. Low risk = Green, Medium risk = Orange, High risk = Red. 94

Table 4.5. Sensitivity analysis of individual criteria as compared to results before sensitivity analysis (as in Table 4.3). Decimal percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk = Orange, High risk= Red). The number of lakes that change A) risk class or B) confidence level for each criterion threshold change is also indicated, and the number

of times a lake changes C) risk class or D) confidence level for each criterion threshold change. 96

Table 4.6. Risk levels for potentially dangerous lakes in the Bolivian Andes as identified by Cook et al. (2016). Decimal percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk = Orange, High risk= Red). 98

Table 5.1. Parameter values used for the three different scenario simulations in HEC-RAS. To estimate Qmax for the Keara Lake, Walder and Costa equation for non-tunnel floods (1996) was used. Evans (1986) was used for the remaining three lakes. Drainage percentage remains at 100% in Keara because the entire lake drained during the 2009 GLOF event. 117

Table 5.2. Satellite images used for DEM extraction. 120

Table 5.3. Potential GLOF impact scenarios for all six villages under threat. 132

Chapter 1

Introduction

1.1 Introduction

This Chapter sets out a short summary of the aim, objectives, and rationale for this study, as well as the scientific background for the work, which is developed in further detail in Chapter 2 - Literature Review. This thesis represents entirely original work undertaken by the author, and each Chapter is organised broadly around academic journal articles that have either already been published (see Appendix 1.1 and 1.2) or are close to submission. At the time of starting this project, several of the supervisory team were already working on the mapping of glacier area change in Bolivia, proglacial lake development, and an initial identification of any such lakes that could be hazardous. These results were published in Cook et al. (2016). Whilst this PhD thesis' author contributed to that work during the early months of this PhD project, the results of that study largely serve as a precursor to this more comprehensive follow-up PhD project. Consequently, the results of Cook et al. (2016) feature in Chapters 1, 2 and 3 and provide important context throughout this thesis. The results presented in Cook et al. (2016) are not presented as original results of this PhD project, although they are partly a product of work undertaken during the early stages of this PhD project.

1.2 Scientific background and rationale for this study

Glaciers in most parts of the world are receding and thinning in response to climate change (Zemp et al., 2015). Mountain glaciers are sensitive indicators of global climate change (Haeberli et al., 2007; Rabatel et al., 2013; Zemp et al., 2015), with most such glaciers in recession around the globe in accordance with global surface temperature increase. This study is concerned with tropical mountain glaciers, which have been studied extensively to understand the rates and magnitudes of environmental change in these regions (Kaser and Osmaston, 2002). The glaciers of the Bolivian Andes, which form the focus of this study, and which represent around 20% of all Andean glaciers (which themselves represent around ~99.5% of all tropical glaciers worldwide), have experienced sustained and widespread shrinkage in recent decades (Soruco et al., 2009; Albert et al., 2014; Cook et al., 2016). Bolivian glaciated area has reduced by around 228.1 ± 22.8 km^2 (43%) from 1986 to 2014 (Cook et al., 2016). As for glacier volumes, Soruco et al. (2009) have estimated changes from 21 glaciers in the Cordillera Real (location shown in Fig. 1.1) from 1963 to 2006, using photogrammetric measurements, and found a loss of 43% ice volume.

Glacier shrinkage could lead to important changes to the Bolivian Andean landscape and for people living downstream from glaciers. Importantly, the two main risks for local populations are:

a) Water shortages. The Bolivian and Peruvian Andes experience distinct wet and dry seasons. During the dry season Andean glaciers are an important contributor to fresh water supply, as well as to hydropower production and mining activities (Carey, 2005; Carey et al., 2014; Soruco et al., 2015).

b) Glacial Lake Outburst Floods (GLOFs). Proglacial lakes develop as glaciers melt, recede and thin (Richardson and Reynolds, 2000; Westoby 2014a; Cook et al., 2016). These lakes can burst, causing severe damage to downstream communities, including possible loss of life.

Peruvian glaciers have been the subject of numerous studies that have focused on glacier shrinkage and associated hazards and risks (e.g., Carey, 2005; Racoviteanu et al., 2008). Indeed, the Peruvian government has taken structural and non-structural measures to tackle these issues; e.g., engineering has been undertaken at several glacial lakes to reduce their outburst flood susceptibility. However, no such study or actions have been pursued in Bolivia. Therefore, there is an urgent need for the development of effective methodologies to assess and/or mitigate the aforementioned risks in Bolivia. Fig. 1.1. illustrates the glaciated Bolivian Cordillera Oriental, extending from northwest to southeast, illustrating this study's area of interest.

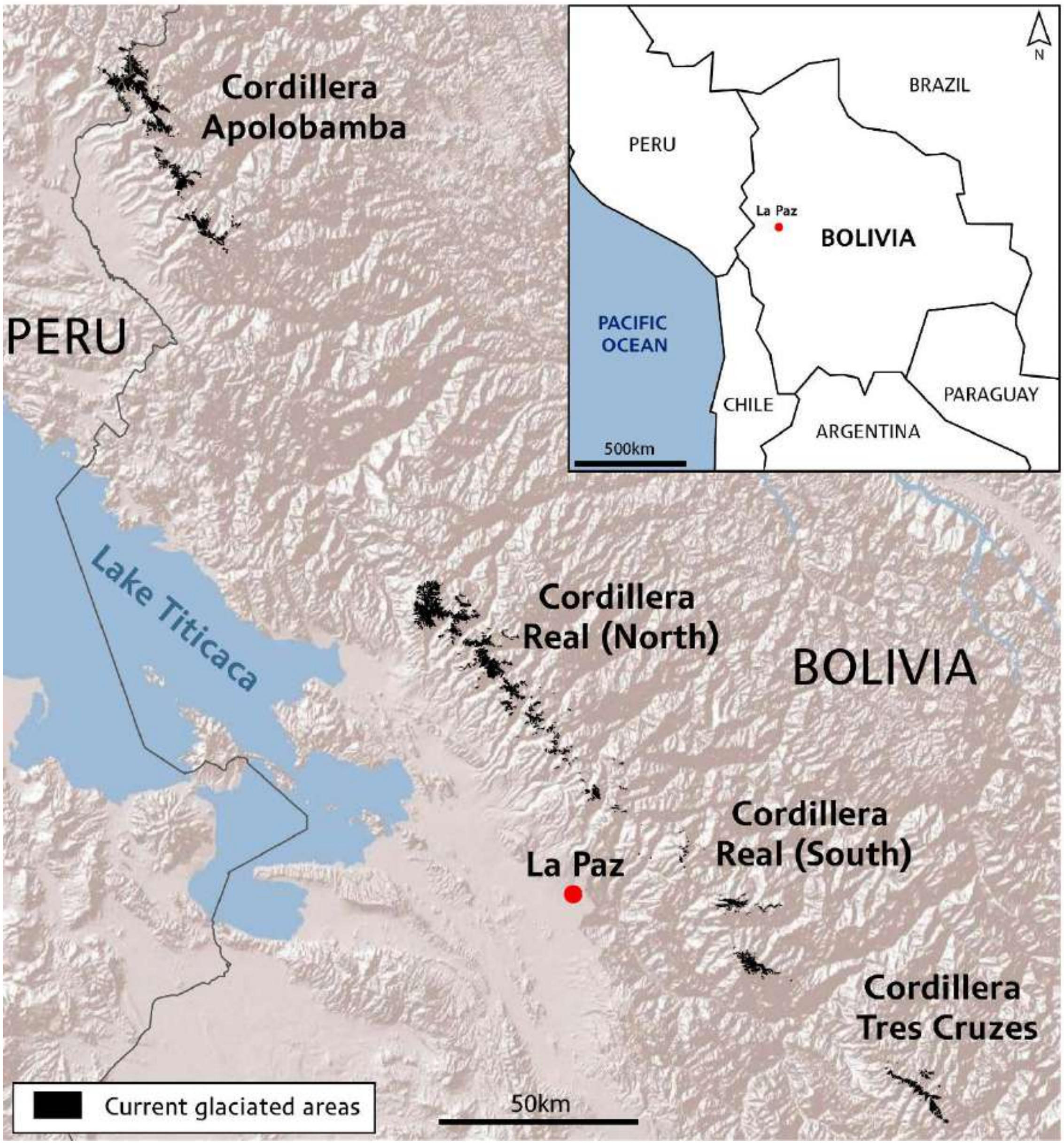


Fig. 1.1. Topographic map of Bolivia and current glaciated areas along the Bolivian Cordillera Oriental. Base map is the Esri World Shaded Relief map (2014).

Research has been undertaken in many regions around the world concerning GLOF risk and hazard assessments, as well as the modelling of past and possible future GLOFs (e.g. Bajracharya., 2007; Allen et al., 2009; Mergili and Schneider, 2011; Worni et al., 2012; Westoby et al., 2014b; Frey et al., 2016; Rounce et al., 2016; Somos-Valenzuela et al., 2016). However, GLOF risk in Bolivia has received very little attention, despite an event having occurred there in 2009 when an ice-dammed lake drained catastrophically, impacting the village of Keara in the Cordillera Apolobamba (Hoffmann and Wegenmann, 2013). Cook et al. (2016) identified 137 proglacial lakes in the Bolivian Andes with 25 of those lakes having population and/or infrastructure downstream, but the effects of potential GLOFs from these lakes have not yet been studied.

1.3 Aims

This project aims:

(1) To evaluate recent glacier change and proglacial lake development (1986 - 2018) in the Bolivian Cordillera Oriental.

(2) To identify glacier bed overdeepenings that could host proglacial lakes in the future, across the same area.

(3) To assess the risk posed by glacial lake outburst floods (GLOFs) across the same area.

1.4 Objectives and thesis structure

In order to achieve the overall aims, this study will focus on the following four objectives:

Objective 1: Determination of glacier area changes and proglacial lake development between 2014 and 2018, building on the results presented by Cook et al. (2016) and using the same methodology as they applied in their paper for the period 1986-2014, in order to observe trends of further shrinkage (i.e. 2014-2018). Next, the Bolivian Cordillera Oriental range divide (i.e. the boundary between east-facing and west-facing glaciated watersheds) will be applied to sub-divide the dataset so that the differences in terms of glacier area between the two sides from 1986 to 2018 are illustrated. Finally, this objective will also focus on the changes to glacier areas between different altitude classes from 1986 to 2018 (i.e. <5000 meters above sea level [m asl.], 5000-5500 m asl. and >5500 m asl.).

Objective 2: Identification of subglacial overdeepenings beneath glaciers (as extracted from 2018 data) will take place, since these locations represent sites for potential future proglacial lake development as glaciers continue to recede. This is achieved using GlabTop, a shear-stress-based approach (developed by Linsbauer et al., 2009, 2012). The inputs required for GlabTop are: a) a Digital Elevation Model (DEM) of the glaciated area of the Bolivian Andes, b) the polygons of the glaciated areas for year 2018, and c) manually digitised flowlines for each glacier. The results of the GlabTop model will be crosschecked with glacier morphological criteria (e.g. crevassing and lateral narrowing of the glacier's flow direction), in order to minimise uncertainty behind the tool's estimations. Next, a first-pass risk assessment will be provided, using a number of qualitative parameters to identify the outburst susceptibility of identified potential proglacial lakes that have not yet emerged from under glaciers and that could be situated upstream from communities. Then a stochastic model, Monte Carlo Least Cost Path (MC-LCP) by Watson et al. (2015) will be applied to estimate potential impacts to the downstream communities from these not yet existing lakes.

Objective 3: Creation of a GLOF risk assessment strategy to identify proglacial lakes that represent the greatest GLOF risk. The approach uses Multi-Criteria Decision Analysis (MCDA) guidelines, and is based on the use of desk-based and no-cost data resources. This method could readily be deployed for any region or proglacial lake context around the world, but is applied here in Bolivia to reveal the highest risk lakes that need to be subject to further more detailed analysis. The software used to evaluate each lake is SMAA-TRI (Stochastic Multi-criteria Acceptability Analysis, http://smaa.fi/), a free-to download and upgraded version of ELECTRE-TRI (Tervonen, 2012). SMAA methods allow the tackling of problems with imprecise information, similar to the criteria used in GLOF multi-criteria assessments.

Objective 4: Modelling of GLOF impacts in the Bolivian Andes through a study of potential GLOF inundation from the proglacial lakes identified as posing the highest risk (from Objective 3). This assessment involves the extraction of a 2m resolution Digital Elevation Model (DEM) from stereo and tri-stereo SPOT 6/7 satellite images, obtained by the European Space Agency. To model the GLOF flow, the 2D hydrodynamic model HEC-RAS 5.0.3 is used. The model is tested against field observations of the 2009 Keara GLOF that occurred in the Cordillera Apolobamba. Finally, after its application to the highest risk proglacial lakes, this modelling approach facilitates an analysis of the approximate number of people potentially exposed to GLOF hazards.

These objectives are addressed in four thesis Chapters. After a general literature review in Chapter (2), the subsequent three Chapters focus on the thesis results and these are all formatted in journal paper structure with introduction, methods, results, discussion and conclusion. Since each of these Chapters possesses its own discussion, the thesis ends with a conclusion and future results section (Chapter 6) summing up the main results. In detail, the thesis is written with the following structure:

- Chapter 2 presents a literature review focusing on glacier change and GLOFs, initially from the global perspective but then narrowing to a focus on the Bolivian Andes. Methodologies used to analyse glacier change and associated risks are also reviewed.
- Chapter 3 addresses objectives 1 and 2, by examining recent glacier area (from 1986 to 2018) using the range divide (east-facing and west-facing glaciated watersheds) and three altitudinal classes (i.e. glaciers situated <5000 m asl., those from 5000 to 5500 m asl. and then ones >5500 m asl.) to identify the main drivers behind these changes. Next, recent proglacial lake development, building on the results from Cook et al. (2016), will take place (from 2014 to 2018). Finally, an estimation of future potential proglacial lake development (from 2018 onwards) as glaciers continue to melt, recede and thin is presented. In addition, a preliminary risk assessment of these future proglacial lakes that could emerge from receding glaciers is also performed.
- Chapter 4 addresses Objective 3 by assessing the criteria that have been used to determine what constitutes a dangerous proglacial lake that could generate a GLOF, by creating an MCDA model that can be used to identify such proglacial lakes in any location around the world. All Bolivian proglacial lakes are assessed using this model to identify those that pose the highest risk to downstream populations and infrastructure, and which are therefore in need of further detailed analysis. This work has been published in *Science of the Total Environment* - see Kougkoulos et al. (2018a) in Appendix 1.1.
- Chapter 5 addresses Objective 4. Here, the impacts of GLOFs from proglacial lakes identified and ranked as the highest risk in Chapter 4 is analysed in detail using hydraulic modelling. This work has been published in *Natural Hazards* - see Kougkoulos et al. (2018b) in Appendix 1.2.

- Chapter 6 will provide overall conclusions and recommendations for future research.

All PhD project outcomes were presented to local NGOs and government officials (e.g. Agua Sustentable, Bolivian Mountain Institute, SENAMHI) at a workshop organised in La Paz, Bolivia, in July 2018 (see Appendix 6.1). Hence, the scientific results of this PhD project have been presented not only in scientific journals, but also through stakeholder engagement.

Chapter 2

Literature review

2.1 Causes and consequences of glacier change

2.1.1 Climate change and global mountain glacier shrinkage

Glaciers around the world are receding and/or thinning due to sustained negative mass balances as a consequence of climate change (Barry, 2006; Benn and Evans, 2010; Rabatel et al., 2013; Zemp et al., 2015). Mountain glaciers are sensitive indicators of global climate change (Haeberli et al., 2007; Rabatel et al., 2013; Zemp et al., 2015), and have responded to negative mass balances through shrinkage – a response that is recognised in most glaciated areas around the world. Mountain glaciers have been studied extensively to understand the rates and magnitudes of environmental change (Kaser and Osmaston, 2002).

Glaciers can be considered as systems, with inputs and outputs, as well as interactions with all four main systems of the Earth (atmosphere, hydrosphere, biosphere and lithosphere). The difference between inputs and outputs to the glacier system is known as the mass balance (Fig. 2.1). Snow and ice from direct snowfall, blown snow, and avalanching from slopes above the glacier surface, represent mass inputs, and are collectively termed accumulation (Benn and Evans, 2010). Ablation refers to all of the processes by which snow and ice are lost from the glacier, including melting, evaporation, sublimation, wind scouring, calving of icebergs, and avalanching of ice blocks from terrestrial ice-cliffs (often referred to as 'dry calving') (Bennett and Glasser, 2009; Benn and Evans, 2010). A net mass balance of zero means that the glacier is in equilibrium, and both its thickness and down-valley extent remain stable. If a glacier experiences sustained negative mass-balance, it will retreat and/or thin; if it experiences sustained positive mass-balance, it will advance and/or thicken (Benn and Evans, 2010). The equilibrium-line altitude (ELA) is the average elevation on the glacier surface where accumulation equals ablation over a 1-year period (Bakke and Nesje, 2011).

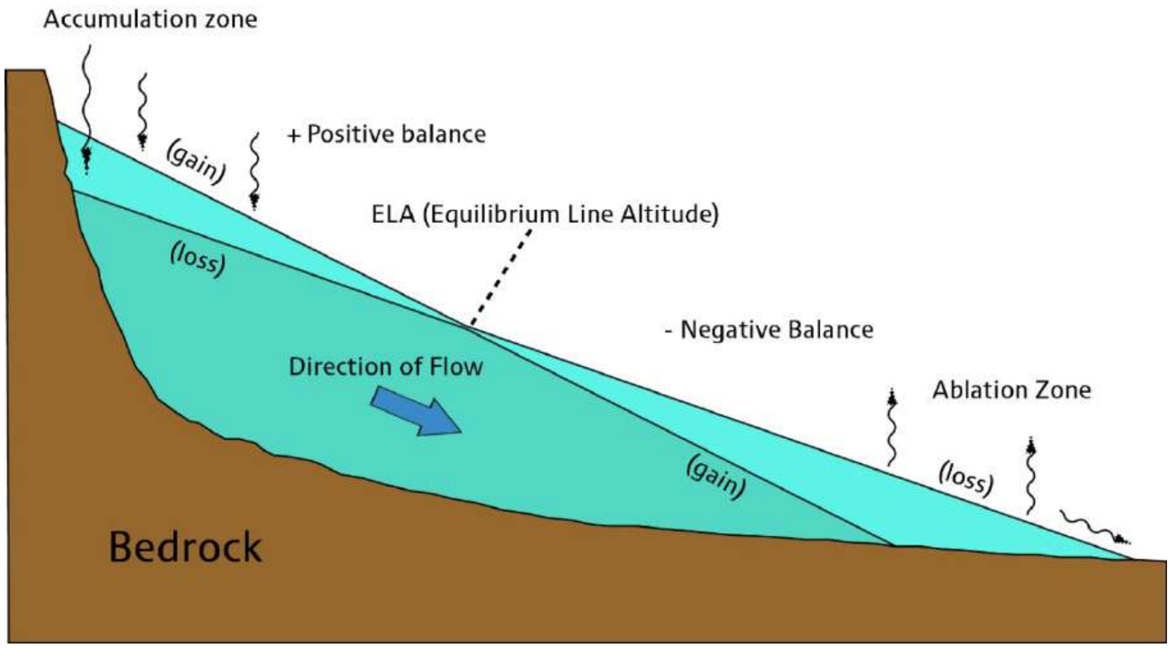


Fig. 2.1. Glacier Mass Balance (Adapted from Bennett and Glasser, 2009)

The global atmospheric temperature increases of around 0.6°C during the past 100 years has caused the disappearance of many mountain glaciers around the world (Levitus et al, 2001; Vaughan et al., 2014). More than 600 glaciers have disappeared over recent decades in the Canadian Arctic and Rocky Mountains, the Andes, Patagonia, the European Alps, the Tien Shan in Central Asia and tropical mountains in South America, Africa and Asia and elsewhere (Vaughan et al., 2014). In Fig. 2.2**,** Vaughan et al. (2014) illustrate three types of glaciers located at different elevations, and their response to an upward shift of the ELA: (a) For a given climate, the ELA has a specific altitude (ELA1), and all glaciers have a specific size; (b) As air temperature increases, the ELA shifts upwards to a new altitude (ELA2), resulting in reduced accumulation and larger ablation areas for all glaciers; (c) After glacier size has adjusted to the new ELA, the valley glacier (left) has lost its tongue and the small glacier (right) has disappeared entirely (Vaughan et al., 2014).

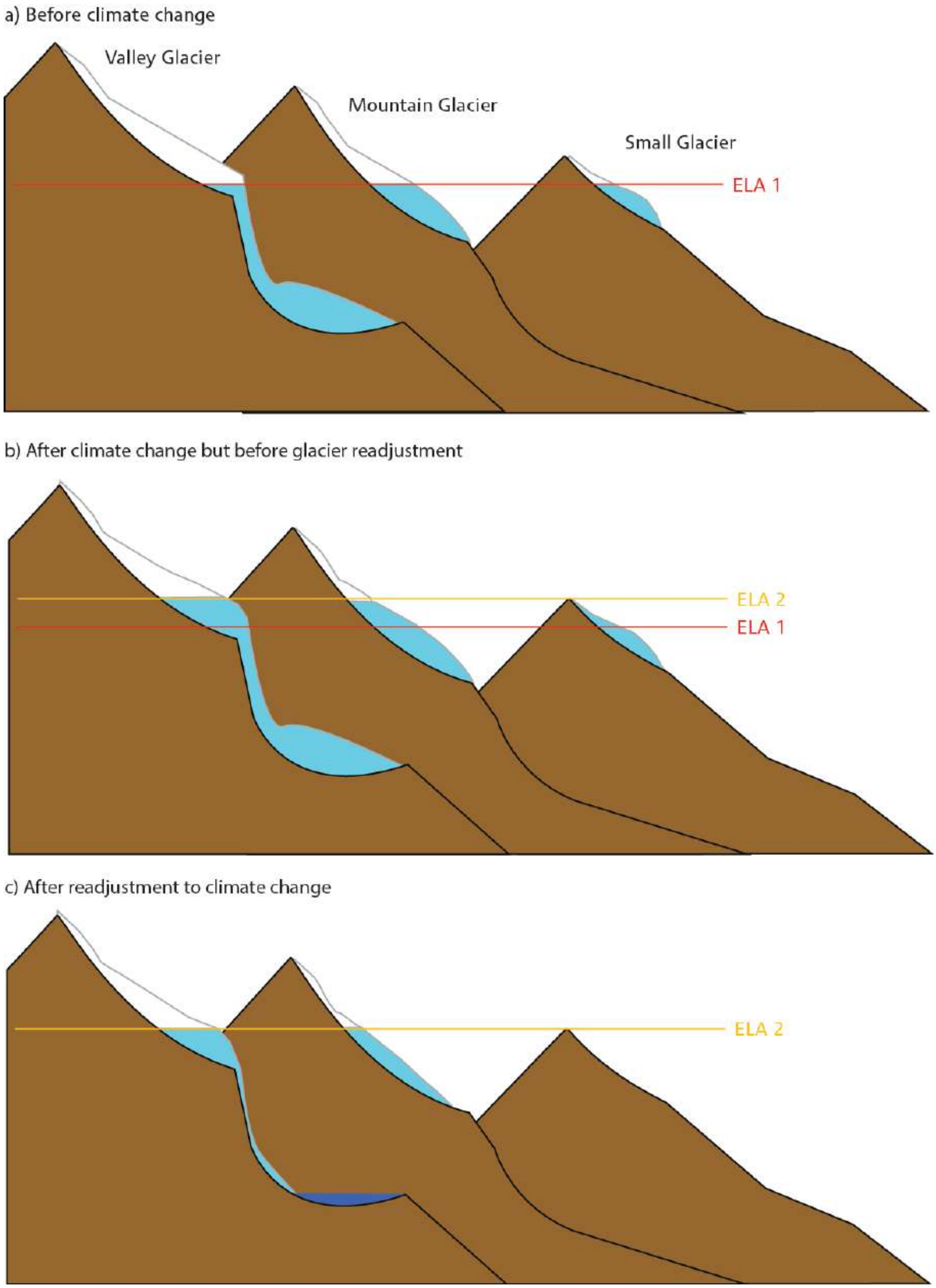


Fig. 2.2. Response to an upward shift of the equilibrium line altitude (ELA) for three glacier types (Adapted from Vaughan et al., 2014). Accumulation zones (white), ablation zones (light blue), meltwater (dark blue).

2.1.2 Characteristics of tropical Andean glaciers

2.1.2.1 Definition of tropical glaciers

Tropical glaciers experience climatic conditions that set them apart from extra-tropical glaciers. Globally, the total area of these tropical glaciers is small (~2500 km^2) and they make up only ~4% of the area of all Earth's mountain glaciers, which is equivalent to about 0.15% of the Earth's total glacier area (Bennett and Glasser, 2009).

According to Kaser (1999), tropical glaciers are defined as follows:

- the glacier must be within the astronomical tropics,
- they are situated in the region where the daily temperature variation exceeds the annual temperature variation,
- they are in the region covered by the Inter Tropical Convergence Zone (ITCZ).

They are sub-divided into two main groups according to climatic conditions (Kaser and Osmaston, 2002):

- The inner tropics, where stable humidity and air temperature mean that accumulation and ablation occur simultaneously throughout the year,
- The outer tropics, where notable accumulation only occurs during the wet season, which is also a period of enhanced ablation. The originality of the outer tropics is that significant ablation can also occur during the dry season and the ELA may lie substantially higher than the 0 °C isotherm (Benn et al., 2005).

Until the late 1990s, knowledge of tropical glaciers lagged behind that of mid- and high-latitude glaciers (Kaser, 1999). It is now known that, in the tropics, the increased mass loss reflects a complex combination of factors related to the energy balance, such as temperature, duration of dry events, precipitation and humidity and melting/sublimation (Kaser and Osmaston, 2002; Coudrain et al., 2005; Thompson et al., 2006). Tropical glaciers receive more solar radiation than mid-latitude glaciers because of higher sun elevation (low latitude) and larger atmospheric transmissivity (high altitude). Furthermore, unlike mid-latitude glaciers, which experience accumulation in winter and ablation in summer, Andean tropical glaciers are subject to ablation throughout the year (Vuille et al., 2008; Rabatel et al., 2013). They accumulate mass during the summer wet season (November to April), and experience enhanced ablation during the winter dry season (May to October) and inter-seasonal periods when solar radiation is more intense (Jordan et al., 1980). As Sicart et al. (2005) underline, any delay in the wet season causes a negative mass balance due to low accumulation and higher ablation. In the outer tropics, the most important factor is the precipitation deficit, while in the inner tropics temperature rise plays a more dominant role, both of which lead to a rise in the snowline altitude that lowers albedo and increases glacier melting (Favier et al., 2004; Schauwecker et al., 2017). Vuille et al. (2015) underlines that the large-scale drivers of Andean glacier retreat, like increasing temperatures or potential changes in the spatiotemporal characteristics of snowfall, altering the glacier's energy and mass balance, have been a wide topic for discussion. Other criteria that play a key role in their evolution are the incoming long-wave radiation, which is related to cloudiness, and air humidity, which influences the energy split between melting and sublimation (Favier et al., 2004; Vuille et al., 2008; Veettil et al., 2016). Furthermore, diurnal variations in temperature are of a greater amplitude than seasonal temperature variation (Kaser and Osmaston, 2002). El Niño–Southern Oscillation (ENSO) phenomena, even though not uniform across the tropical Andes, also play a major role in glacier mass balance in the region and this will be discussed in more detail in section 1.3.

2.1.2.2 The Andes

The vast majority of tropical glaciers (99.64%) are situated in the Andean mountains of South America; the remainder include 0.25% on the African mountains of Rwenzori, Mount Kenya and Kilimanjaro, and 0.11% in the Irian Jaya region in New Guinea (Kaser and Osmaston, 2002; Vuille et al., 2018).

Rabatel et al. (2013) observed that over a period of 35 years, in the tropical Andes, glaciers situated below 5400 m asl. lost volume twice as fast as those above 5400 m asl. Permanently cold temperatures above a certain altitude mean that snow cover does not melt, since elevation matches the uppermost altitude reached by the equilibrium-line even during very negative mass balance years (Vuille et al., 2008; Rabatel et al., 2013).

Observations on length and area variations from glaciers in Ecuador, Peru and Bolivia illustrate rapid retreat of tropical Andean glaciers since the little ice age (LIA). Concerning local climate, air temperature in the Andes has increased by approximately 0.1 °C per decade (in the second half of the 20th century), with only two of the last 20 years being below the 1961–90 average (Vuille et al., 2008). In the same period, precipitation has increased slightly in the inner tropics and decreased in the outer tropics (Vuille et al., 2008; Rabatel et al., 2013). Projections for the 21st century (IPCC scenario A2) are that temperature is predicted to rise by more than 4 °C at elevations above 4000 m asl. (Bradley et al., 2006; Urrutia and Vuille, 2009; Rabatel et al., 2013).

In conclusion, glaciers are currently retreating everywhere in the tropical Andes, and this shrinkage is much more pronounced for small glaciers at low altitudes that do not have a permanent accumulation zone; these glaciers are very likely to disappear in the coming years/decades (Rabatel et al., 2013).

2.1.3 Bolivia

2.1.3.1 Climatic setting

The Bolivian Cordillera Oriental (Fig 1.1) is located in the central Andes, where the climate is characterized by both latitudinally and orographically enhanced changes in precipitation (e.g. Aceituno, 1988; Garreaud and Wallace, 1997). North of ∼18°S, the large-scale atmospheric circulation over South America leads to a strong regional precipitation gradient, with up to 4 m yr^{-1} rainfall. The Andes act as a topographic barrier between the humid Amazon Basin and the more arid Pacific margin to the west (Lenters and Cook, 1995; Insel et al., 2010). In the EC, a clear difference between wet and warm (austral summer from November to April) and dry and cold (austral winter from May to October) seasons is observed (Veettil et al., 2017; Veettil and Kamp, 2017). In recent studies, the climate of the Bolivian Cordillera Oriental is classified as one of southern wet outer tropics (Sagredo & Lowell 2012; Sagredo et al. 2014; Veettil et al., 2017, Veettil and Kamp, 2017). Temperature variations are observed (at 2 m above glacier surface at around ± 4°C throughout the year (Veettil et al., 2017). Monthly precipitation rates seem to be important in the Bolivian Cordillera Oriental, especially due to the moisture transport from the Amazon Basin by the mechanism of the Amazonian monsoon during October–April (Garreaud et al., 2009; Veettil et al., 2017). Furthermore, while in the northern outer tropics the precipitation values seem to be relatively constant over the last 30 years, the southern outer tropics exhibit larger interannual precipitation variability (Sagredo et al., 2014).

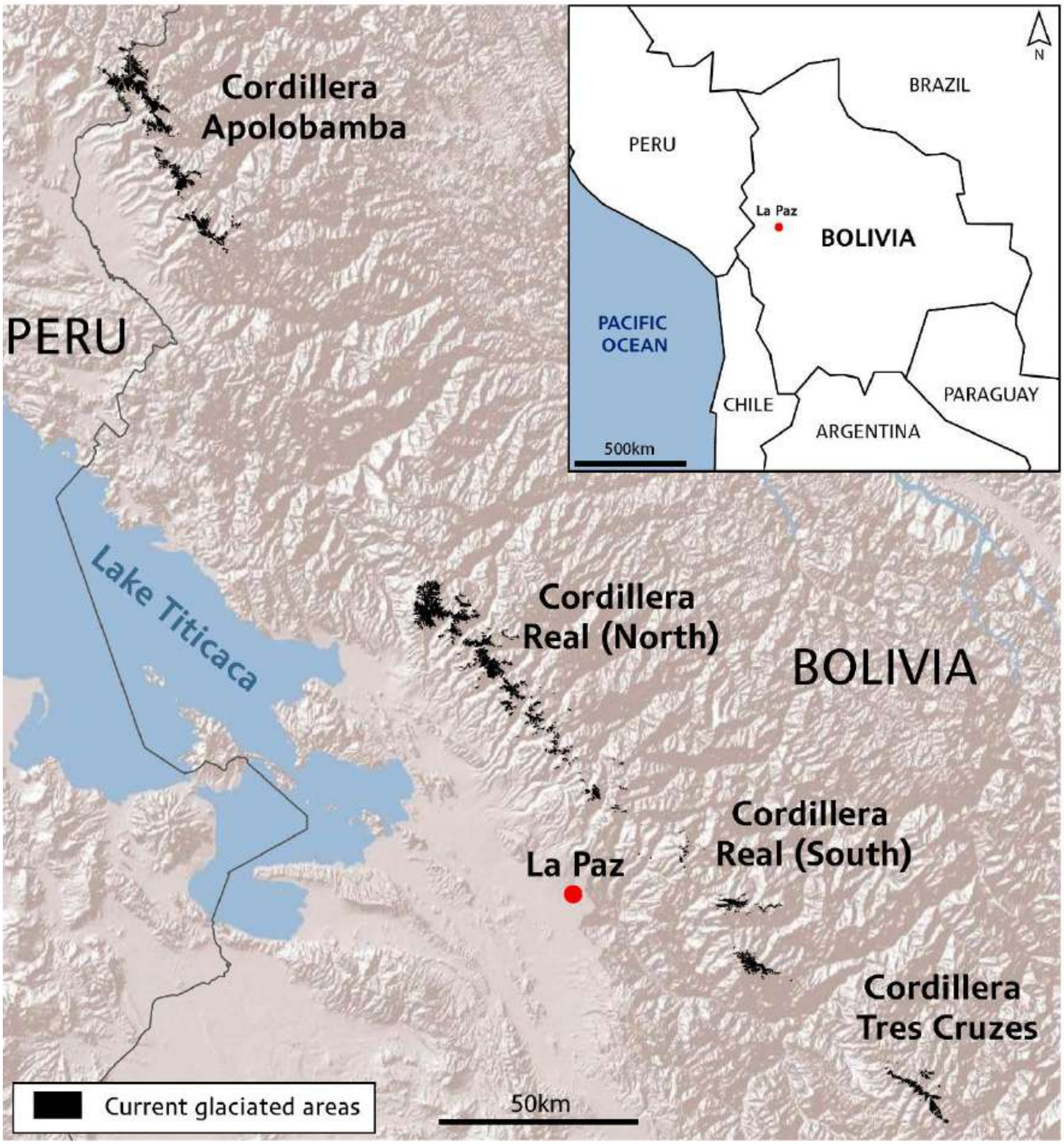


Fig. 1.1. Topographic map of Bolivia and current glaciated areas along the Bolivian Cordillera Oriental. Base map is the Esri World Shaded Relief map (2014).

2.1.3.2 Current state of knowledge of Bolivian glaciers

Of the Andean glaciers, 71% are located in Peru, 20% in Bolivia, 4% in Ecuador, and 4% in Colombia and Venezuela (Kaser, 1999; Bury et al., 2011; Rabatel et al., 2013). Peruvian glaciers have been the subject of more extensive studies focusing on induced hazards occurring from their shrinkage (e.g. Carey, 2005; Racoviteanu et al., 2008). Furthermore, the Peruvian government has taken structural and non-structural measures to tackle these issues (e.g. Lake Palcacocha engineering actions).

Despite the regional importance of Bolivian glaciers, research to monitor their extent and response to climate change has been rather limited. Detailed mass balance and modelling studies have been performed for a few glaciers, such as Zongo Glacier (e.g. Francou et al., 1995; Sicart et al., 2011; Réveillet et al., 2015; Soruco et al., 2015). Other studies have documented the demise of Chacaltaya Glacier, which disappeared in 2009 (Ramirez et al., 2001; Soruco et al., 2015). At a broader scale, Jordan et al. (1980) and Jordan (1991, 1998) developed the first inventory of glaciers in Bolivia. Soruco et al. (2009) calculated a volumetric reduction of 43% for 21 glaciers of the Cordillera Real over the period 1963–2006 (location shown in Fig. 1.1), whilst Albert et al. (2014) demonstrated that glaciers of the small range of Tres Cruces had lost approximately half of their surface area between 1975 and 2009 (location shown in Fig. 1.1). Soruco et al. (2009) also observed a 48% decline in surface area of 376 glaciers investigated in the Cordillera Real from 1975 to 2006. The same trend is also observed across the approximatively same year span in other glaciated regions of the world, such as the Alps, where the estimated glaciated area shrinkage during 1954–2003 was on the order of 51% (Diolaiuti et al., 2011). Nevertheless, in the Nepalese Himalaya, the area losses between 1963 and 2009 remained lower at around 20% (Budhathoki et al., 2011), principally because of a high representation of debris-covered glaciers that tend to thin more rapidly than they recede.

Cook et al. (2016) offered the first complete quantification of glacier change across the entire Bolivian Andes. Their results revealed an overall areal shrinkage of 228.1 ± 22.8 km^2 (43.1 %) across the Bolivian Cordillera Oriental, between 1986 and 2014. Shrinkage was greatest in the Tres Cruces region (47.3 %), followed by the Cordillera Apolobamba (43.1 %) and Cordillera Real (41.9 %) (location shown in Fig. 1.1).

The El Niño Southern Oscillation (ENSO) also plays a role in influencing glacier change in the region. In Bolivia, during the warm (El Niño) period, negative mass balances are observed to be linked to a deficit of precipitation during the summer/wet period, which directly affects the albedo and the melting rates at the glacier surface (Coudrain et al., 2005). In this intense melting period, the snow/rain limit moves up to 5000 m, which results in decreased accumulation (Coudrain et al., 2005). On the other hand, La Niña years tend to be wetter and colder, slowing or arresting mass loss and leading to neutral or positive mass balances (Coudrain et al., 2005; Vuille et al., 2008, Veettil et al., 2018). In order to better understand the complexities of this glacioclimatological process, other criteria need to be taken into account (e.g. seasonal snowfall, wind speed, and glacier sublimation characteristics) (Veettil et al., 2018).

2.1.3.3 Concerns about glacier change in Bolivia

Glacier shrinkage, as well as Bolivia's status as the poorest country in South America, led to the country being very vulnerable to the impacts of climate change (Oxfam, 2009). Rapid glacier retreat in the Andes will disrupt the water cycle in glacier-dependent basins, affecting water regulation and availability (Vergara et al., 2007; Rangecroft et al., 2016). Therefore, an urgent need for awareness and management of water resources, incorporating both social and natural sciences, has arisen not just for Bolivia, but also for the entire Andean region (Bradley et al., 2006; Carey et al., 2017). Indeed, it is estimated that only 56% of Bolivia's rural population have access to safe water (Rangecroft et al., 2013), meaning that the sustainability of glaciers is a significant concern in the broader context of poverty and vulnerability to climate change. More than 80% of freshwater available for downstream populations and ecosystems in the semi-arid tropics and subtropics originates in mountains (Messerli, 2001). More precisely, the glaciers of the Andean cordilleras play a significant role as freshwater resources during the dry season (~6 months per year), in both the lowlands and altiplanos, for agriculture, drinking water, hydropower production and mining activities (Carey, 2005; Carey et al., 2014). Soruco et al. (2015) focused on the contribution of glacier runoff to water supply in La Paz. They assessed the glacier water supply between 1963 and 2006 over annual and seasonal timescales and estimated that glaciers of the Cordillera Real supply approximatively 15% of potable water for the capital (14% in the wet season, 27% in the dry season). La Paz's twin adjacent city, El Alto, is the poorest city in Bolivia and by 2009 demand for water in the area had already outstripped supply, a situation that could become a lot worse in the face of demographic pressures; its population is predicted to double by 2050, reaching two million people (Buxton et al., 2013).

In a more recent study, Buytaert et al. (2017) focused on evaluating Andean water resources linked to glaciers. They found that under drought conditions user reliance on glacial meltwater is high (up to 3.92 million domestic users, 2096 km^2 of irrigated land, and 732 MW of hydropower production in the driest month of a drought year). Nevertheless, they underline that the number of users relying constantly on water resources with a high (>25%) long-term average contribution from glacial meltwater remains low (391,000 domestic users, 398 km^2 of irrigated land, and 11 MW of hydropower production).

As two of South America's fastest growing cities, water stresses are expected to be amplified in La Paz and El Alto by glacier recession, population increase, and projected increases in rural-to-urban migration driven by climate change and westernization of lifestyles (Rangecroft et al., 2013, 2016). These projected changes in demand, combined with changes to water supplies, are expected to have critical negative impacts on water security, affecting environmental, economic and social systems (Bradley et al., 2006; Rangecroft et al., 2016). There is also some evidence that more isolated mountain communities in Bolivia are suffering increasingly from the adverse effects of glacier recession and changing meltwater supply in response to climatic warming (Oxfam, 2009), although it does not yet appear to be a direct driver of rural-to-urban migration (Raoul, 2014).

Hydropower accounts for approximately 32% of electricity generation in Bolivia (World Bank, 2010), and maintaining the integrity of the industry is important for local communities. La Paz, like many Andean cities, derives some of its electricity from hydropower generation, which depends to some extent on glacial meltwater generation. Some researchers have expressed concern that power generation during the dry season will become unreliable due to low water flows (Raoul, 2014), although this issue requires further quantitative study.

2.2 Proglacial lake development: location, formation and evolution

An important, but almost unexplored, issue in Bolivia is the development of lakes associated with glacier recession. In many glaciated mountain ranges, glacier shrinkage since the Little Ice Age has been accompanied by the development of proglacial, ice-marginal and supraglacial lakes impounded by moraine, ice, landslide or bedrock dams (Röhl, 2008; Benn and Evans, 2010; Jansky et al., 2010; Thompson et al., 2012; Carrivick and Tweed, 2013; Emmer et al., 2014; Iturrizaga, 2014; Westoby et al., 2014a; Westoby et al., 2014b; Cook and Quincey, 2015; Nie et al., 2017). Proglacial lakes exist in all currently glaciated regions of the world and there is also evidence of their existence in formerly glaciated areas (Carrivick and Tweed, 2013). Some of these lakes represent a glacial lake outburst flood (GLOF) hazard, as moraine dam integrity reduces over time, leading to dam failure, and because mass movements of ice, snow and rock from surrounding valley slopes impact lakes, leading to wave-overtopping of moraine and bedrock dams (Clague and Evans, 2000; Richardson and Reynolds, 2000; Hubbard et al., 2005; Westoby et al., 2014a; Westoby et al., 2014b). A typology of these lakes is important in order to gain a better understanding of their structure and analyse their GLOF-generating potential.

Bedrock–dammed lakes: form in depressions excavated by glacial erosion that emerge as a glacier retreats (Cook and Swift, 2012; Emmer et al., 2014; Haeberli et al., 2016). These are not strictly 'dammed' lakes, but lakes occupying overdeepenings, or so-called 'embedded lakes' (Mergili and Schneider, 2011; Emmer et al., 2016). The dam of the lake is composed of bedrock, and thus is considered in most cases to be relatively stable (Huggel et al., 2004) (Fig. 2.3).

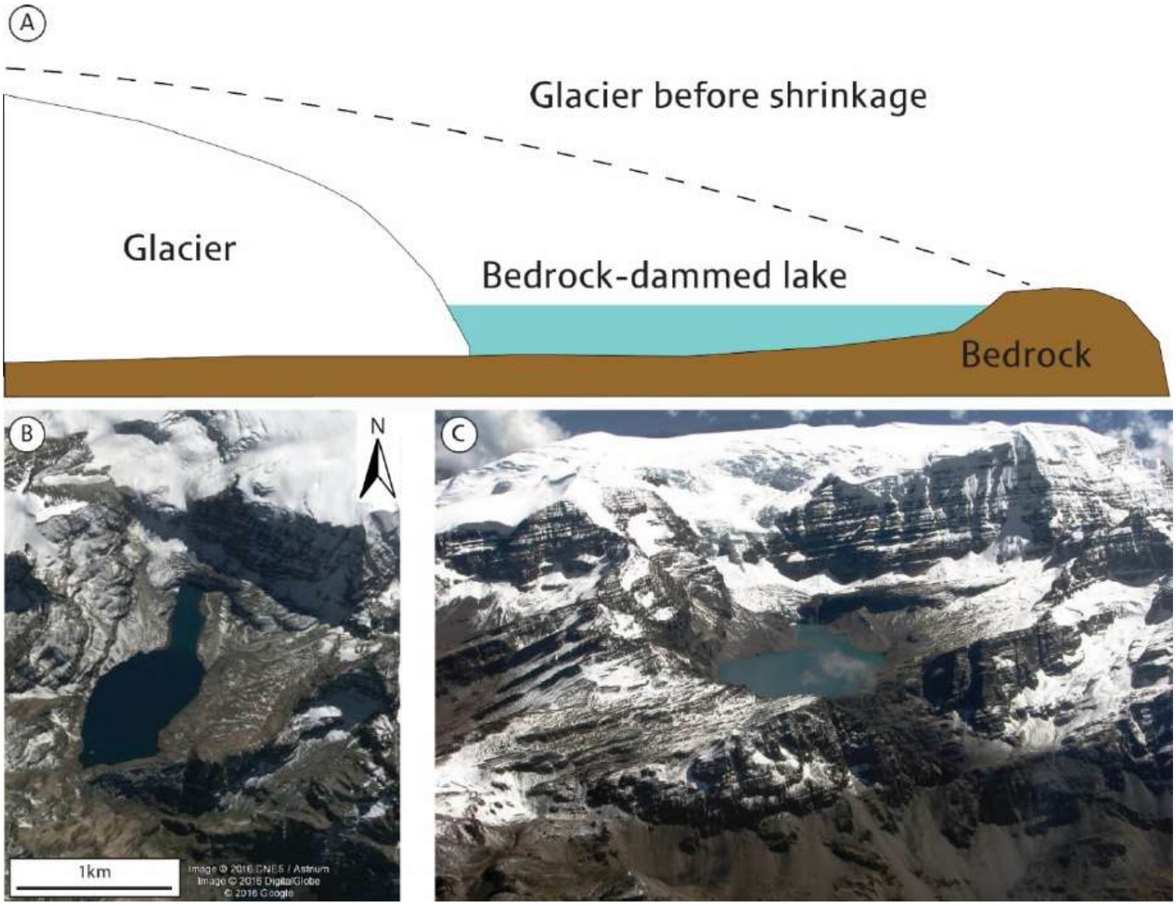


Fig. 2.3. Example of a bedrock-dammed lake (Laguna Arkhata / coordinates: 19 K 624521 8172040): (A) Evolution of the lake in longitudinal view, (B) Google earth image (2016), (C) Photo of the lake (tantan tanuki)

Moraine-dammed lakes: form behind an impounding moraine dam as a glacier retreats and thins. They expand into topographic lows formerly occupied by ice or major meltwater channels and lakes can grow rapidly, fed by both precipitation and glacial melt-water (Wang et al., 2011; Carrivick and Tweed, 2013; Iturrizaga, 2014) (Fig. 2.4). In addition, supraglacial lakes that often develop on debris-covered glaciers as debris-charged glacier snouts can become separated from more rapidly ablating ice up-glacier; in these circumstances, ice-cored and non-ice cored moraine then serves as an effective barrier to meltwater runoff, leading to proglacial lake development (e.g. Ageta et al., 2000; Stokes et al., 2007). Through time, the growth of supraglacial lakes and the rapid backwasting of bordering ice cliffs may lead to merging with nearby lakes, and increased chances to form potentially dangerous moraine-dammed lakes (Sakai et al., 2000; Watanabe et al., 2009; Mertes et al., 2016).

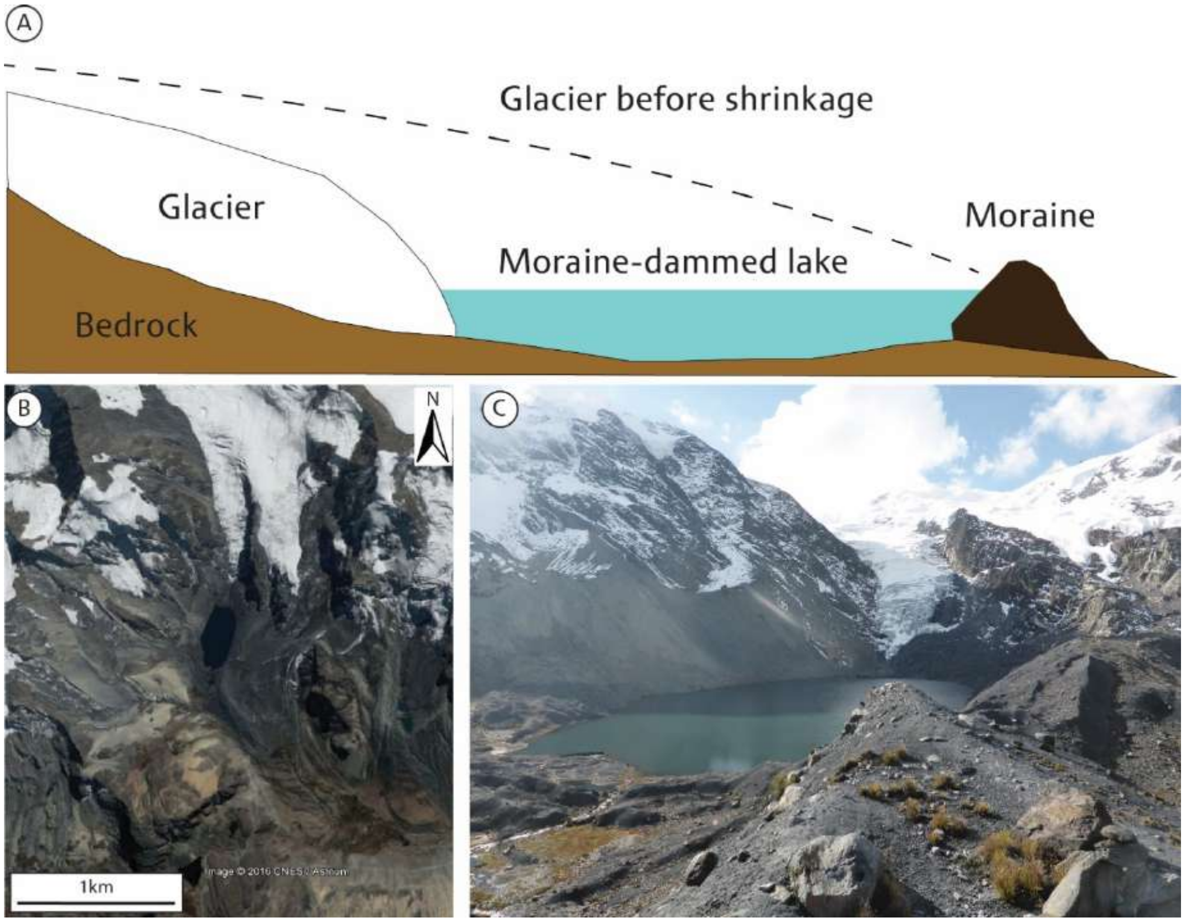


Fig. 2.4. Example of a moraine-dammed lake (Pelechuco / coordinates: 19 L 481205 8365591): (A) Evolution of the lake in longitudinal view, (B) Google earth image (2016), (C) Photo of the lake (SJ. Cook, 2015)

Ice-dammed lakes: Are generally considered to be one of the least stable types of lake (Korup and Tweed, 2007; Emmer et al., 2014). The filling and drainage of these ice-dammed reservoirs is controlled by the imbalance between two water fluxes: input controlled predominantly by meltwater production, and output through a subglacial drainage system, the evolution of which is controlled by the water pressure in the reservoir. Hence, these reservoirs are similar to subglacial drainage systems in terms of water pressure and discharge (Kingslake and Ng, 2013; Kingslake, 2015) (Fig. 2.5).

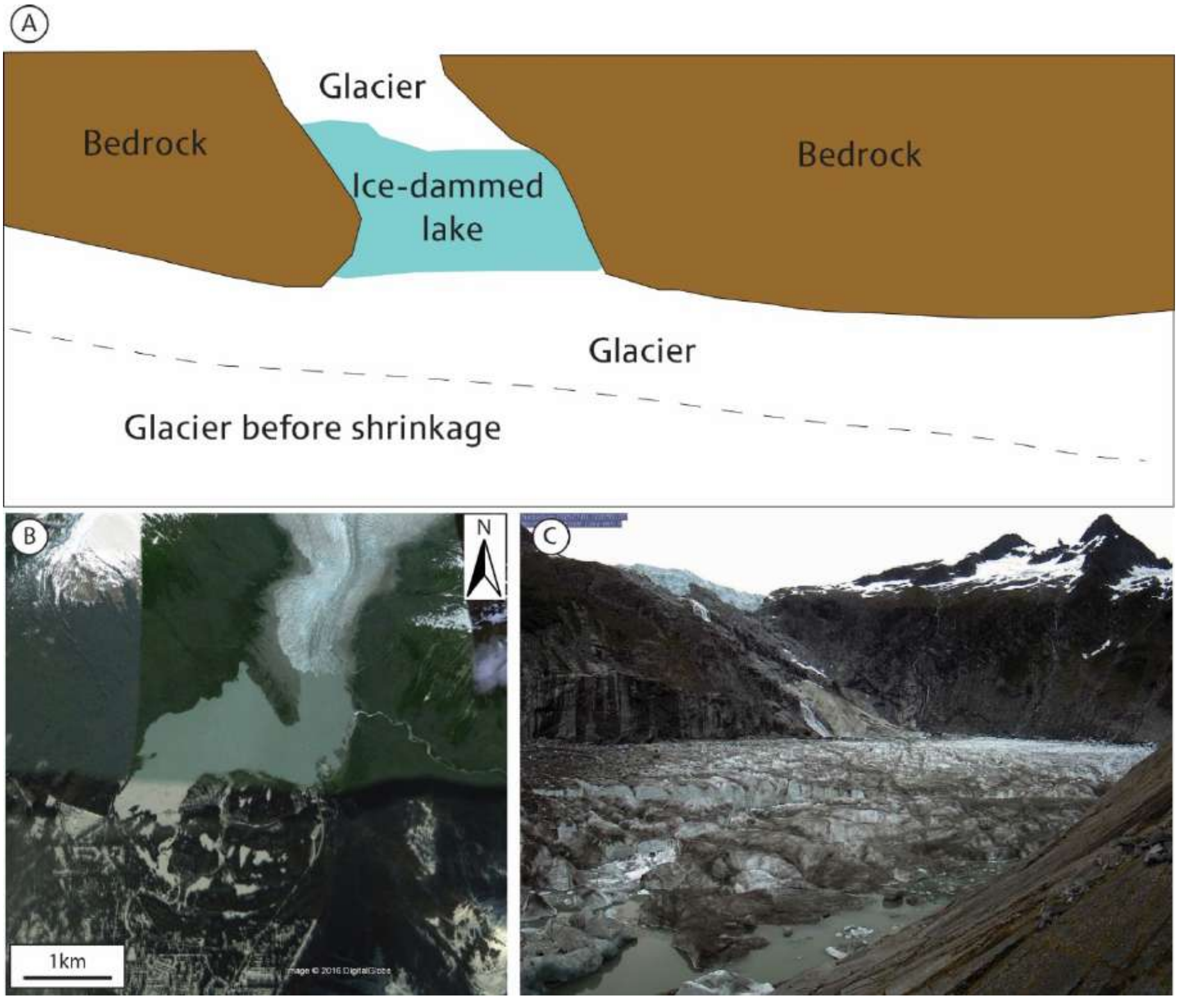


Fig. 2.5. Example of an ice-dammed lake (Mendenhall Lake in Alaska / coordinates: 8 V 525112 6475896): (A) Evolution of the lake in plan view, (B) Google earth image (2016), (C) Photo of the lake (U.S. Geological Survey webcam)

Landslide-dammed lakes: their formation in glacial environments is difficult to predict and is usually related to the slopes being left unsupported because of glacier retreat (Korup and Tweed, 2007; Carrivick and Tweed, 2013). Increases in slope angle and relief, coupled with the loss of internal friction and cohesion of slope materials, prepare slopes for failure (Carrivick and Tweed, 2013). This type of setting is common in geologically active areas such as the Hindu Kush Himalayas, where earthquakes occur and slopes are steep. Large landslide dams are often caused by complex landslides that start as slumps and transform into rock or debris flows or avalanches (Fig. 2.6).

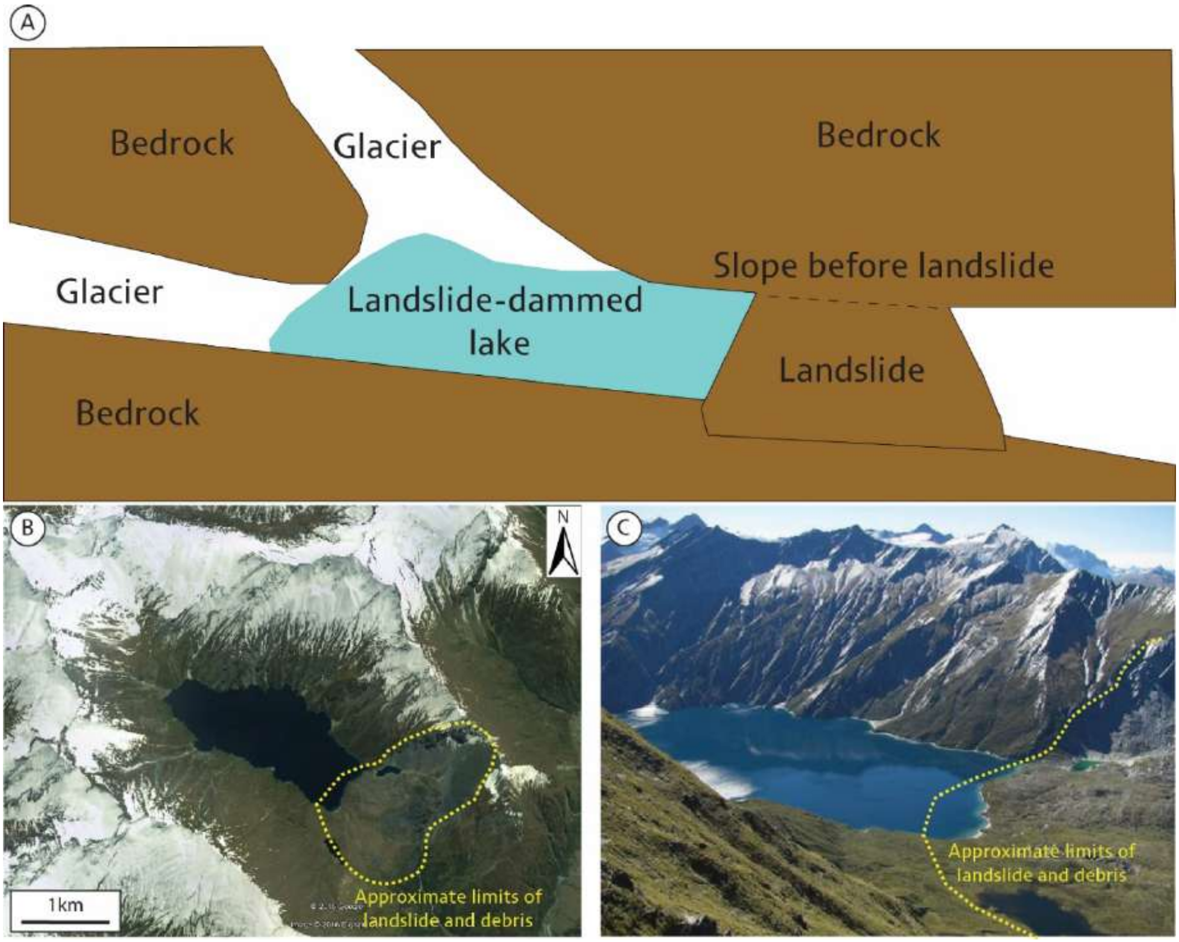


Fig. 2.6. Example of a landslide-dammed lake (Loch Nagar in New Zealand / coordinates: 59 G 309609 5059766): (A) Evolution of the lake in plan view, (B) Google earth image showing approximate landslide limits (2016), (C) Photo of the lake showing approximate landslide limits (nickorama)

In conclusion, Carrivick and Tweed (2013) underline that numerous studies have documented an increase in the number and size of lakes in nearly all glaciated regions of the world (the European Alps, the Caucasus, Iceland, South America and the Himalaya). Therefore, this lake development trend could help to reduce water scarcity over the next few decades as glaciers disappear (Komori, 2008; Mergili and Schneider, 2011; Wang et al., 2015), since these lakes could be used as potential reservoirs for water resources (Haeberli et al., 2016). Nevertheless, it also indicates that GLOFs will represent an increasingly important threat in high-mountain areas (Bolch et al., 2008; Watanabe et al., 2009; Hoffmann and Weggenmann, 2013).

2.3 Definition, causes, and consequences of GLOFs

2.3.1 Incidences of GLOFs around the globe

Carrivick and Tweed (2016) observed that, in terms of historical and modern glacier floods occurring worldwide, 70 % are from ice-dammed lakes, 9 % are from moraine-dammed lakes, 16 % are from an unknown dam type/trigger, and 3 % are triggered by volcanic activity (nearly all of the latter taking place in Iceland). In another study, Vilímek et al. (2013) compiled a database of more than 500 GLOF events based on scientific research articles, non-scientific reports and regional studies. They identified 380 GLOFs from ice-dammed lakes, 130 GLOFs from moraine-dammed lakes and several GLOFs originating from bedrock-dammed lakes or lakes with combined dams. Harrison et al. (2018) identified 165 GLOFs from moraine-dammed lakes that have been recorded from the start of the 19th century. Of these, 160 (97%) GLOFs occurred since the start of the 20th century, when glacier recession and climate warming became more pronounced. In Bolivia, three main types of dammed lakes are, or have been recently, present (ice, moraine, and bedrock) and will be studied during this project.

Even though there is abundant geomorphological, sedimentological and human evidence that numerous GLOF events have also taken place in the past, rising interest in GLOFs started taking place not more than 2 decades ago (Emmer et al., 2016). Moreover, an exponential increase in the number of GLOF-related research items published in the Web of Science (WOS) database is revealed, with >50% of the research items being published since 2008 (Emmer, 2018). Therefore, as a new research topic concerning important population numbers around the world, novel risk and hazard assessments must be developed and already existing ones must be improved, in order to tackle these issues in the face of the glacier shrinkage predicted over the next decades.

2.3.2 Triggering causes and consequences of GLOFs according to dam types

Lake drainage is mostly caused by direct and indirect slope movements associated with deglaciation. Increasing instability of steep, high-mountain slopes is observed with potential to produce rock and ice avalanches that affect lakes and could trigger GLOFs (Richardson and Reynolds, 2000; Carey et al., 2012; Haeberli, 2013; Vilímek et al., 2013; Emmer et al., 2014). These events can produce river flows that are orders of magnitude larger than peak discharges from intense precipitation events, with major consequences for landscape change, human infrastructure and life (Benn and Evans, 2010).

Emmer and Vilímek (2014) have defined five triggering mechanisms for GLOFs occurring from bedrock-, moraine- and landslide-dammed lakes, as follows:

1) Dam overtopping following rapid slope movement into the lake,
2) Dam overtopping following a flood wave originating in a lake situated upstream,
3) Dam failure resulting from rapid slope movement into the lake,
4) Dam failure following the flood wave originating in a lake situated upstream,
5) Dam failure following strong earthquake.

Bedrock dams are considered stable except in regions of very high seismicity. Bedrock dams can be overtopped, however, where a GLOF is triggered by a slope movement into the lake. Vilimek et al. (2015) give a notable example from Lake 513 in the Chucchun Valley of the Cordillera Blanca (Peru). This incident took place in 2010 and caused no fatalities; nevertheless, some houses, roads, bridges and an important water treatment facility were destroyed. The rather low extent of damage is due to the fact that the valley is not densely populated and some villages were out of reach of the debris flow. It was a considerable event due to the large amount of material transported down the valley (Fig. 2.7).

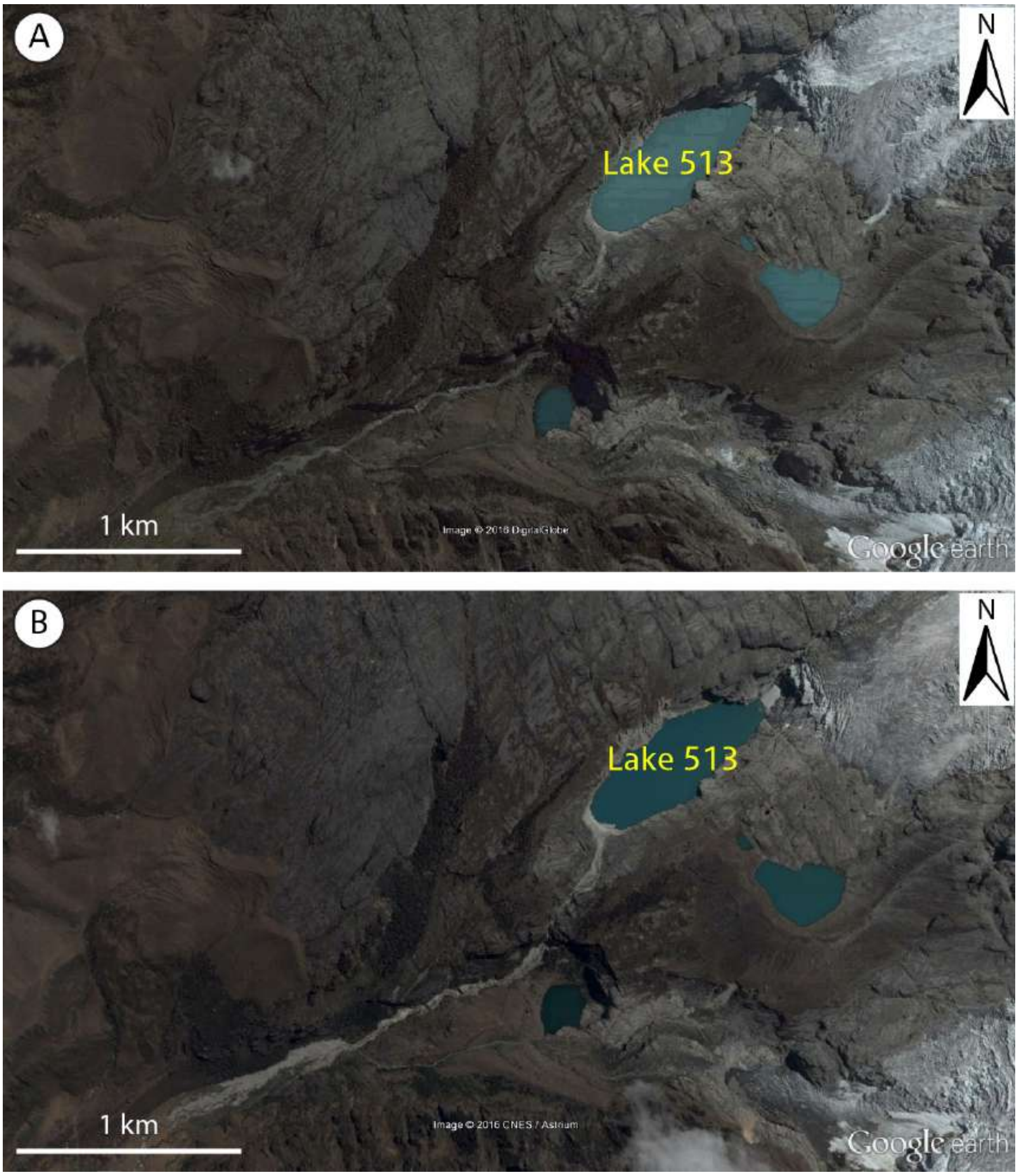


Fig. 2.7. Lake 513 GLOF, Peru (coordinates: 18L 219791 8980650): (A) lake and stream before the incident (2002), (B) lake and stream after the incident (2013).

Proglacial lakes that form behind moraines are potentially dangerous because they are dammed by unconsolidated and poorly sorted material, that is susceptible to piping and degradation that enhances dam failures, and at the same time the melting of dead ice inside the moraine-dam further weakens the dam. In addition, moraine-dammed lakes are often in direct contact with the glaciers from which potential icefalls into the lake represent the most frequent trigger for outburst floods (Clague and Evans, 2000; Richardson and Reynolds, 2000). Concerning moraine and landslide-dammed lakes, previously mentioned triggers also apply (Emmer and Vilímek, 2014). One notable example of a GLOF due to moraine-dam failure occurred in 1941 in the

Cordillera Blanca (Lake Palcacocha), Peru, which severely damaged the city of Huaraz and caused as many as 1800 deaths. It destroyed infrastructure and agricultural land all the way to the coast (Benn and Evans, 2010; Carey et al., 2012; Emmer and Cochachin, 2013; Somos-Valenzuela et al., 2016). An example of the GLOF is illustrated in Fig. 2.8.

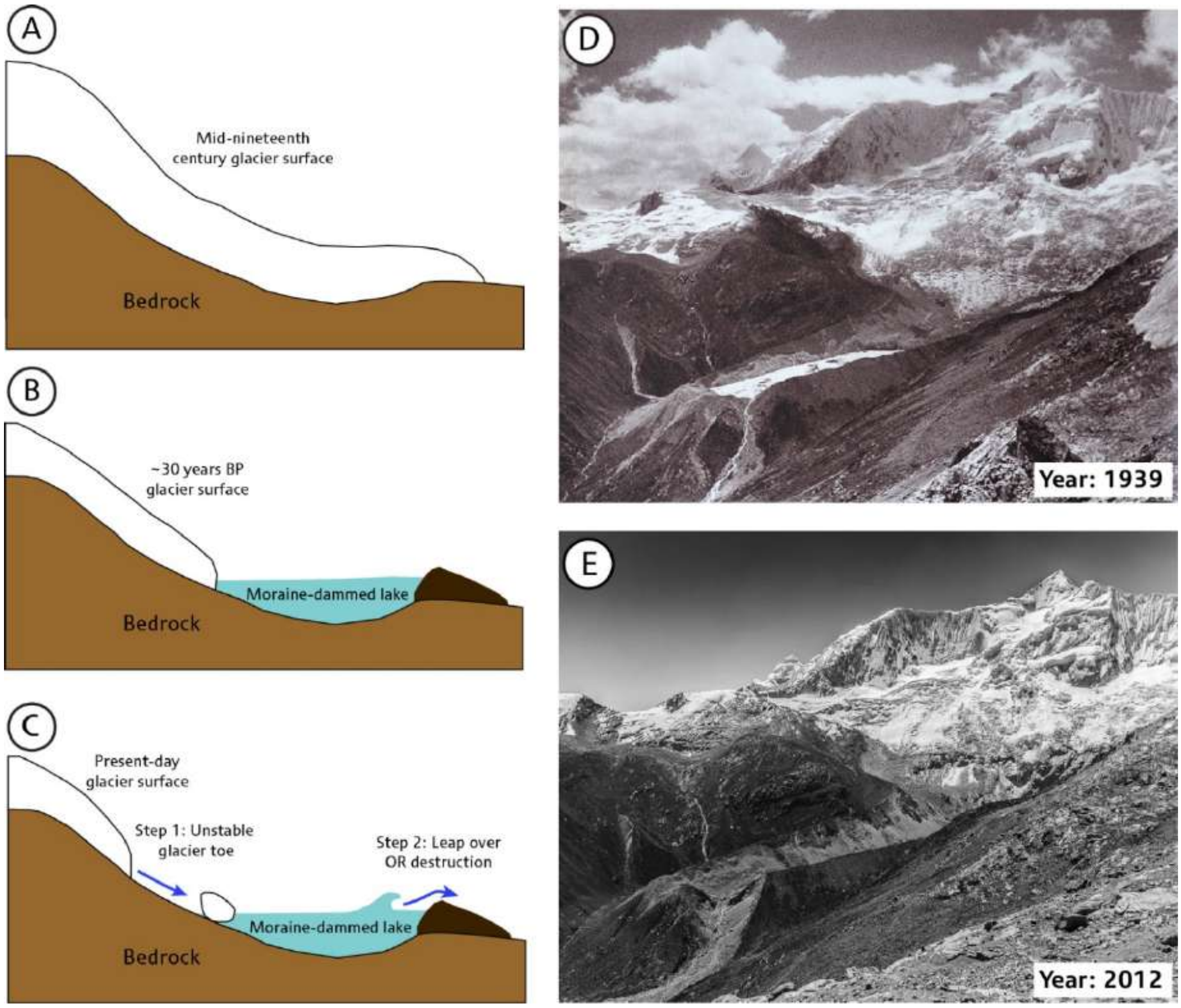


Fig. 2.8. Palcacocha Lake GLOF, Peru (coordinates: 18 L 238608 8960350): (A) glacier before recession and lake creation, (B) glacier recession and moraine-dammed lake creation, (C) collapse of an unstable part of the slope leaping over or destroying the dam, (D) Photo before the 1941 event (German and Austrian Alpine Club DuOAV), (E) Photo 71 years after the event (Sergiu Jiduc).

Another example of GLOFs from moraine-dammed lakes is Dig Tsho, in front of Langmoche Glacier, Nepal, which occurred in 1985 and caused five deaths and damage to important infrastructure (Vuichard and Zimmermann, 1986; Benn and Evans, 2010). Nevertheless, generally the damage of GLOFs in the Himalaya (compared to the Peruvian Andes) has been lower, because the events have taken place in less populated areas. Because of the remoteness of many glacial lakes, there is often a lack of basic data of potentially dangerous areas and the local communities at risk.

Ice dams tend to fail suddenly, and this can be a major concern for downstream communities. According to Tweed and Russell (1999), there are nine mechanisms that can trigger glacier-impounded lake outbursts. Seven of these mechanisms may apply in Alpine environments. The mechanisms are outlined in Table 2.1.

Table 2.1. Summary table of ice-dammed lakes by triggering mechanism and cause of drainage (Adapted from Tweed and Russell, 1999)

Trigger mechanism	Cause of drainage
Seismic activity	Weakening of ice dam by tectonic activity; water escapes via weaknesses.
Overspill	Ice-dammed lake depth exceeds either: (1) ice-dam height; or (2) lowest topographic control.
Glen mechanism	Hydrostatic head of water in ice-dammed lake exceeds ice over-burden pressure.
Flotation	Ice-dammed lake depth exceeds 90% of the ice-dam height effecting flotation of ice-dam by lake water. Lake water then escapes.
Syphoning	Reduction in pressure in the retaining glacier's internal drainage system to which the ice-dammed lake is connected. Water is effectively syphoned out through the glacier through pre-existing conduits.
Subglacial cavity formation	Opening of cavities at the ice/bed interface facilitates drainage. The opening of cavities can be cause by rapid basal ice flow due to an increase in water supply. Excess water may be supplied by ablation, rainfall or water pocket release.
Subaerial breaching	Breach of ice dam or breach widening of the contact between ice and the valley wall. The mechanism is correlated with lakes formed by the advance of a tributary valley glacier into a main valley.

Hoffmann and Weggenmann (2013) give a notable example of a GLOF that took place in 2009 in Bolivia, at a lake (19 L 481932 8377262) situated upstream from the village of Keara (Fig. 2.9).

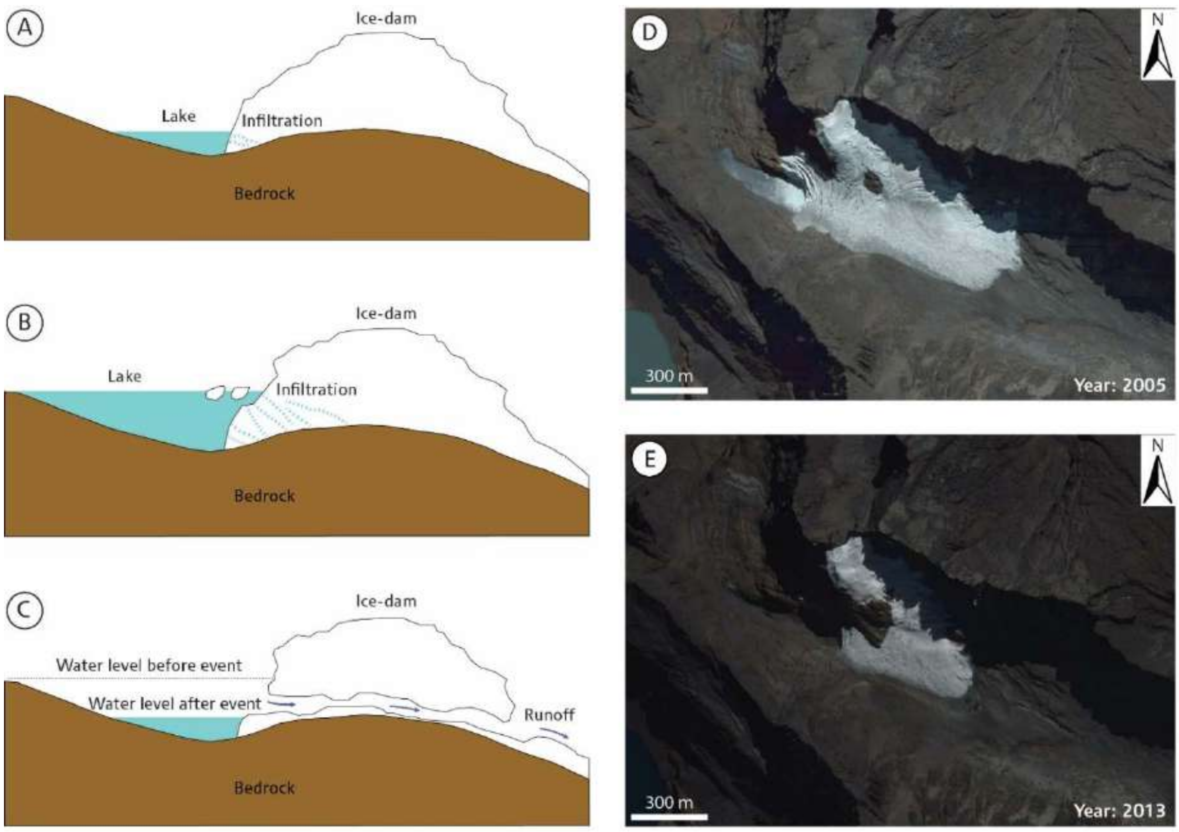


Fig. 2.9. Keara Lake GLOF, Bolivia (coordinates: 19 L 481932 8377262): (A) lake and infiltration through the ice-dam, (B) increased infiltration leading to calving and icefalls, (C) sudden failure of the ice dam

After its complete drainage within a few minutes, a wave of water moved downstream, flooding cultivated fields, destroying several kilometres of a local dirt road, washing away pedestrian bridges and killing a number of farm animals (Hoffmann and Weggenmann, 2013) (Fig. 2.10).

Fig. 2.10. (A) Incision and boulder transport due to the GLOF, (B) disaster aftermath (Martín Apaza Ticona)

In other locations, several studies have shown that glacier recession has been accompanied by an increase in the number and size of proglacial lakes (Komori, 2008; Carrivick and Tweed, 2013; Hanshaw and Bookhagen, 2014; López-Moreno et al., 2014; Wang et al., 2015; Watson et al., 2015), raising concerns that glaciated mountain regions are becoming more hazardous with respect to GLOFs.

It is widely accepted that moraine-dammed and ice-dammed lakes may exhibit a high dam failure potential, whereas bedrock-dammed lakes are generally stable (Huggel et al., 2004). Furthermore, it is important to underline that all types of dammed lakes are highly dynamic and the changes they undergo can create complex and interdependent processes and impacts (Carrivick and Tweed, 2013). For example, a GLOF from a moraine-dammed lake at Chamdo, in the Boschula mountain range of Tibet, triggered a large landslide that led to the formation of a landslide-dammed lake (Wang et al., 2011), which in turn could generate further floods. In conclusion, as Anacona et al. (2015) underline, the risk of GLOFs cannot be eliminated unless lakes are fully drained.

2.4 Definitions, perceptions and concepts of risk

2.4.1 Disaster risk management: different approaches

The definition of risk of disaster is a compound function of the natural hazard and the number of people, characterised by their varying degrees of vulnerability to that specific hazard, who occupy the space and time of exposure to the hazard event (Wisner et al., 2004) (Fig. 2.11). As Wisner et al. (2004) underline, until vulnerability came to be a main component of the scientific definition of risk and disasters, completely different perceptions of risk and disasters used to dominate the field. On the one hand, there exists a naturalist or physicalist view, in which nature is to blame, and on the other hand there is the so-called “environmental determinism”, in which human misinterpretation of nature, because of limited rationality and heuristics of the human mind, leads to a series of unwanted interactions.

More recently, the United Nations International Strategy for Disaster Reduction (UNISDR) reported that there is no such thing as a 'natural' disaster, but only natural hazards. Disasters often follow natural hazards. A disaster's severity depends on how much impact a hazard has on society and the environment. The scale of the impact in turn depends on the choices humans make, which affects themselves and their ecosystem. These choices can affect any kind of sector: agriculture, politics, finance or even construction. These decisions will make the individual and/or the community more or less vulnerable to a disaster. The aforementioned approach to disaster risk management was used for years by engineers and researchers around the globe.

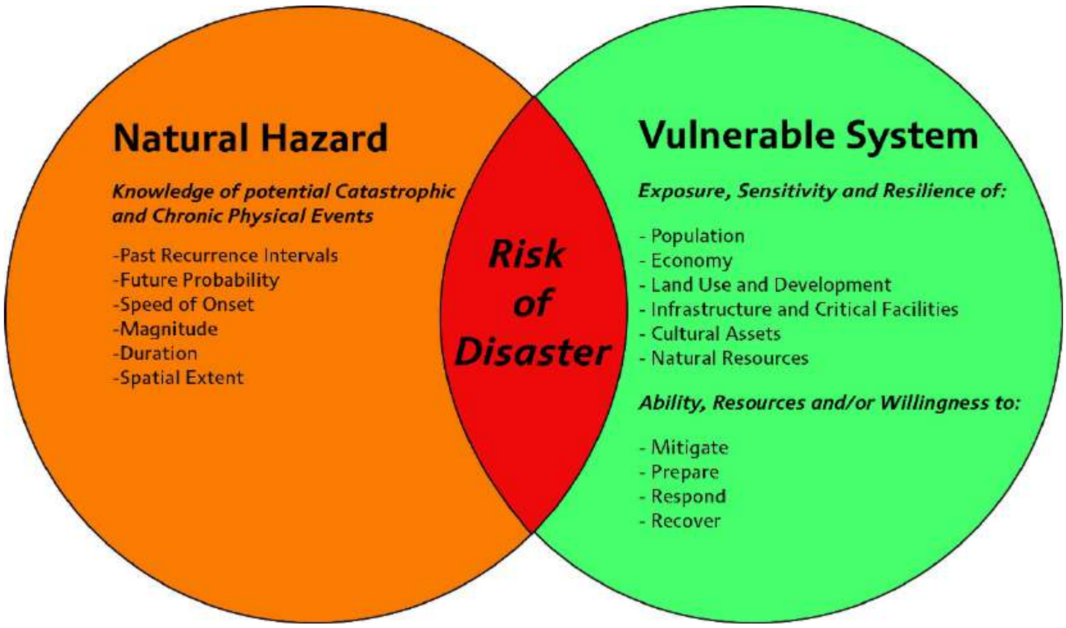


Fig. 2.11 Disaster Risk Management (Adapted from Wood-USGS, 2011)

Moreover, in exploring the role of the natural hazard scientist, it is useful to consider four stages in the natural hazards event: (1) quiescence, (2) imminent threat, (3) the event itself, and (4) the recovery stage back to 'life as normal'. This process can also be expressed as a cycle (Fig. 2.12):

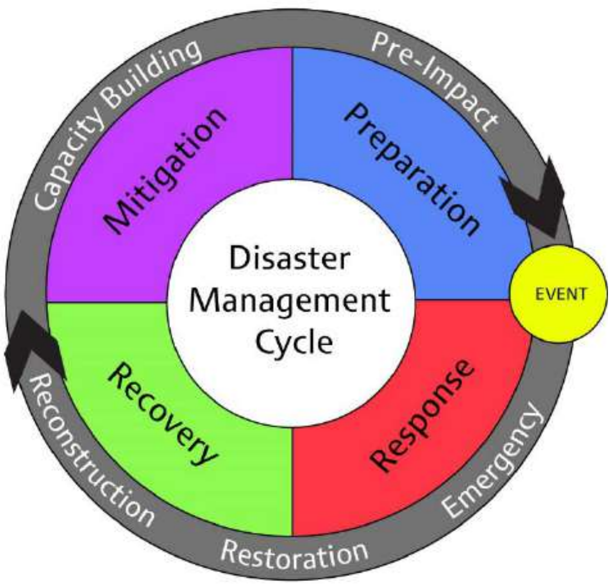


Fig. 2.12. The disaster management cycle (Moe and Pathranarakul, 2007; Janssen et al., 2010)

The relative timescales vary greatly between different natural hazards. Each stage poses different challenges for natural hazard scientists, but the assessment and communication of uncertainty and risk is central to all (Hill et al., 2012).

The role of climate change in increasing both our vulnerability to natural hazards (e.g. through sea-level rise, droughts and floods) and our uncertainty about future natural hazard frequency is significant (Mitchell et al., 2006; Cutter and Finch, 2008; Jennings, 2011). A large number of reports on disasters and increases in the uptake of insurance are other factors that might make these trends appear more pronounced. Responses to natural hazard threats and events are firmly within the human world, where many factors relating to the collective and individual human behaviour influence the scale of an emergency and the extent to which it might become a disaster.

2.4.2 A new definition of risk

Since in different scientific fields (e.g. finance, health sciences, earth sciences and engineering), the definition of risk can take different forms, the international organization for standardization (ISO) has proceeded with a normalised definition.

On the 13th of November 2009, ISO 31000 was published and provides a standard on the implementation of risk management; an updated version was published in February 2018 – ISO 31000:2018. The purpose of ISO 31000 is to be applicable and adaptable for any public, private or community enterprise, association, group or individual (Purdy, 2010). Accordingly, the general scope of ISO 31000 - as a family of risk management standards - is not developed for a particular industry group, management system or with a specific subject matter field in mind, rather to provide best practice structure and guidance to all operations concerned with risk management. Furthermore, the definition of "risk" is no longer "chance or probability of loss", or the product of hazard and vulnerability (e.g. IPCC, 2014), but ***"the effect of uncertainty on objectives"*** thus causing the word "risk" to refer to positive possibilities, as well as negative ones. Further definitions about the concept of risk (e.g. hazard, vulnerability and resilience) can be found in the official glossary of the Society for Risk Analysis (SRA) (2015).

In the case of glacial lakes as sources of outburst floods, several examples can strengthen this definition: glacial lakes can be seen to be an important source of water reservoir for surrounding populations, but also as a threat, since catastrophic GLOF events can be damaging for these communities (World Disasters Report-IFRC, 2014). In conclusion, the regulation of glacial lakes can, in some cases, generate co-benefits in terms of disaster risk reduction, water resource management and energy production, but the legal, social, cultural and political constraints for implementation remain considerable (Haeberli et al., 2016; Vuille et al., 2018).

Chapter 3

Glacier change, proglacial lake development and future GLOF risk in Bolivia

3.1 Introduction

There have been very few studies of glacier change in Bolivia, but there has been recent progress in understanding the evolution of these glaciers over the late twentieth and early twenty-first centuries. Most recently, Cook et al. (2016) mapped glacier change from multi-temporal Landsat satellite imagery across the Bolivian Eastern Cordillera (EC). Overall, they found that glaciers shrunk in area by around 43.1 % (228.1 ± 22.8 km^2) from 1986 to 2014, with the greatest shrinkage in the Cordillera Tres Cruces (47.3 %), followed by the Cordillera Apolobamba (43.1 %) and Cordillera Real (41.9 %). Ongoing monitoring of glacier change since the end of the 1986-2014 study period is required and little is known about the broad controls (e.g. altitude, range divide) on glacier mass balance in the region.

In addition, as Bolivian glaciers have receded and thinned, numerous proglacial lakes have developed, as has been the case in many other deglaciating mountain ranges. For the first time, Cook et al. (2016) quantified changes in the number and size (area) of these proglacial lakes in Bolivia from 1986 to 2014. They found that the total number of lakes within 500 m from glacier margins increased from 145 to 225 lakes (55 %) whereas lake area increased from 6.33 ± 0.63 to 8.73 ± 0.87 km^2 (38 %). Since these lakes can pose a GLOF risk to downstream communities, Cook et al. (2016) suggested that monitoring of future glacier and lake development should take place.

There have been several previous studies for other deglaciating mountain ranges to determine the locations of subglacial overdeepenings that will emerge in the future with ongoing glacier recession (e.g. Frey et al., 2010; Linsbauer et al., 2016; Drenkhan et al., 2018; Rashid and Majeed, 2018). However, very few studies have attempted to estimate GLOF risk from potential future lakes, and no such studies exist for Bolivia. The only example of such a study is that of Colonia et al. (2017) who found 201 overdeepenings beneath Peruvian glaciers, many of which could hold sufficient volumes of water to represent a concern as a GLOF hazard. These authors then used the Modified Single Flow (MSF) to model a possible future GLOF from one of these potential future lakes.

In light of the requirements for ongoing monitoring and further study outlined above, this Chapter has the following four objectives designed to investigate recent Bolivian glacier change, proglacial lake evolution and future GLOF risk:

a) To quantify recent glacier area change and proglacial lake development across the Bolivian Cordillera Oriental from 2014 to 2018, thereby extending the monitoring period of Cook et al. (2016).
b) To explore the influence of altitude and range divide (i.e. east-facing, west-facing) on glacier area change from 1986 to 2018.
c) To estimate ice-thickness in order to model potential future lake development (2018 onwards) as glaciers recede and thin.
d) To provide a first-pass risk assessment for any potential future lakes.

3.2 Methods

3.2.1 Mapping glacier area and proglacial lake changes in the Bolivian Cordillera Oriental (2014 – 2018)

The census period for mapping glacier area changes extends from 2014, using the 2014 glaciated area shapefiles from Cook et al. (2016), to 2018 using atmospherically corrected Landsat 8 imagery (Table 3.1). The glaciated areas of the Peruvian side of the Cordillera Apolobamba have not been considered in this study. The same methodology for glaciated area extraction and uncertainty analysis was applied in this study as was applied by Cook et al. (2016) in order to ensure comparability of results. Images were selected from the dry season when snow cover (which could be confused for glacier ice) would have been at a minimum, and with as little cloud cover as possible.

Table 3.1. Summary of Landsat scenes used in this study.

Scene ID number	Path/row	Date	Sensor	Satellite	Cloud cover (%)
LC80020702018194LGN00	002/070	13/07/2018	OLI & TIRS	8	2.27
LC80010712018235LGN00	001/071	23/08/2018	OLI & TIRS	8	18.4
LC82330722018148LGN00	233/072	28/05/2018	OLI & TIRS	8	19.21
LC80020702014215LGN00	002/070	8/3/2014	OLI & TIRS	8	8.81
LC80010712014128LGN00	001/071	5/8/2014	OLI & TIRS	8	19.78
LC82330722014153LGN00	233/072	6/2/2014	OLI & TIRS	8	8.62

The same automatic ice cover identification technique as used by Cook et al. (2016) was employed here, although manual correction of the output was also undertaken as necessary. First, lakes that had been misidentified as ice cover were removed from the glacier shapefiles. Secondly, all glacier polygons smaller than 0.05 km^2 were removed as they probably represented snow patches rather than glacier ice (c.f. Bolch et al., 2011; Burns and Nolin, 2014; Cook et al., 2016). Thirdly, the areas identified as ice cover were checked against imagery in Google Earth. Any other misidentified features (e.g. snow patches, areas of moraine or debris-covered ice, etc.) were then edited manually in ArcGIS 10.3.1.

The uncertainty associated with automatic mapping was estimated following the method of Hanshaw and Bookhagen (2014), which was also used by Cook et al. (2016). They assume that mapping errors are Gaussian, i.e. that ~69 % (1σ) of pixels will be subject to error. Uncertainty is calculated as Eq.3.1:

$$Error\ (1\sigma) = (P/G) \cdot 0.6872 \cdot G^2/2 \qquad (3.1)$$

Where *P* is the measured glacier perimeter, and *G* is the grid cell size. Uncertainties calculated using Equation 3.1 are ~10 %. Paul et al. (2013) found that error for measuring clean-ice glaciers with automated methods, such as in this study, are < 5 % for glaciers larger than 1 km^2, and an overall error of 2 - 6 %.

Concerning proglacial lake identification, the same lake extraction method employed by Cook et al. (2016) was applied here on the Landsat 8 (2018) imagery (Table 3.1). Lake extents were digitised manually with reference to both Landsat false colour composites, and NDWI (Normalised Difference Water Index) rasters (Huggel et al., 2002; Bolch et al., 2011). All visible lakes were mapped where they occurred within approximately 2 km of the glacier margins. As with glacier mapping, the lake mapping uncertainty is ~5–10 % (Cook et al., 2016).

In order to produce a first-order estimation of proglacial lake volumes, measured lake area is multiplied by averaged or integrated lake depth (Cook and Quincey, 2015). Cook et al. (2016) used the dataset of Cook and Quincey (2015) to derive an empirical relationship (Eq. 3.2) between lake depth and area that is specific to moraine-dammed lakes:

$$D = 0.097A^{0.4375} \qquad (3.2)$$

where *D* is mean lake depth in metres (m) and *A* is lake surface area in square metres (m^2). Equation (3.2) can be used to predict mean lake depth, which can be multiplied by measured lake area to calculate lake volume. As did Cook et al. (2016), Eq. 3.2 was used here for both moraine- and bedrock-dammed lakes since there is no known equation to estimate depths from the latter.

3.2.2 Range divide and altitudinal controls on glacier change

There is a strong precipitation gradient across the Andes, which may play a role in the mass balance of Bolivian glaciers and their response to climate change over time (Garreaud et al., 2009). Likewise, glacier dynamics may vary with altitude. Hence, glacier area change from 1986 to 2018 (Cook et al., 2016 and this study) is investigated here with respect to these two potentially important controls.

First, all watersheds of the three cordilleras (Apolobamba, Real, Tres Cruces) were extracted from the SRTM DEM using Arc Hydro Tools 2.0. To investigate broad differences across the Andean range divide (which runs approximately North East to South West), watersheds were grouped according to whether they fell on the Pacific (West) side, or the Amazonian (East) side (Fig. 3.1).

Second, the glaciated areas of the Bolivian Andes were sub-divided into altitudinal classes. Several studies conducted on the Zongo glacier have reported an ELA from 5000 m asl. to 5500 m asl. during the years 1994 to 2006. Therefore, to observe glacier area and losses at different altitudes, the range was divided into categories around the approximate 5000-5500 m asl. ELA zone. Specifically, elevation classes were <5000 m asl. (likely representing the ablation zone), 5000-5500 m asl. (the ELA), and >5500 m asl. (likely representing the accumulation zone) (Fig. 3.1 and Fig. 3.2)

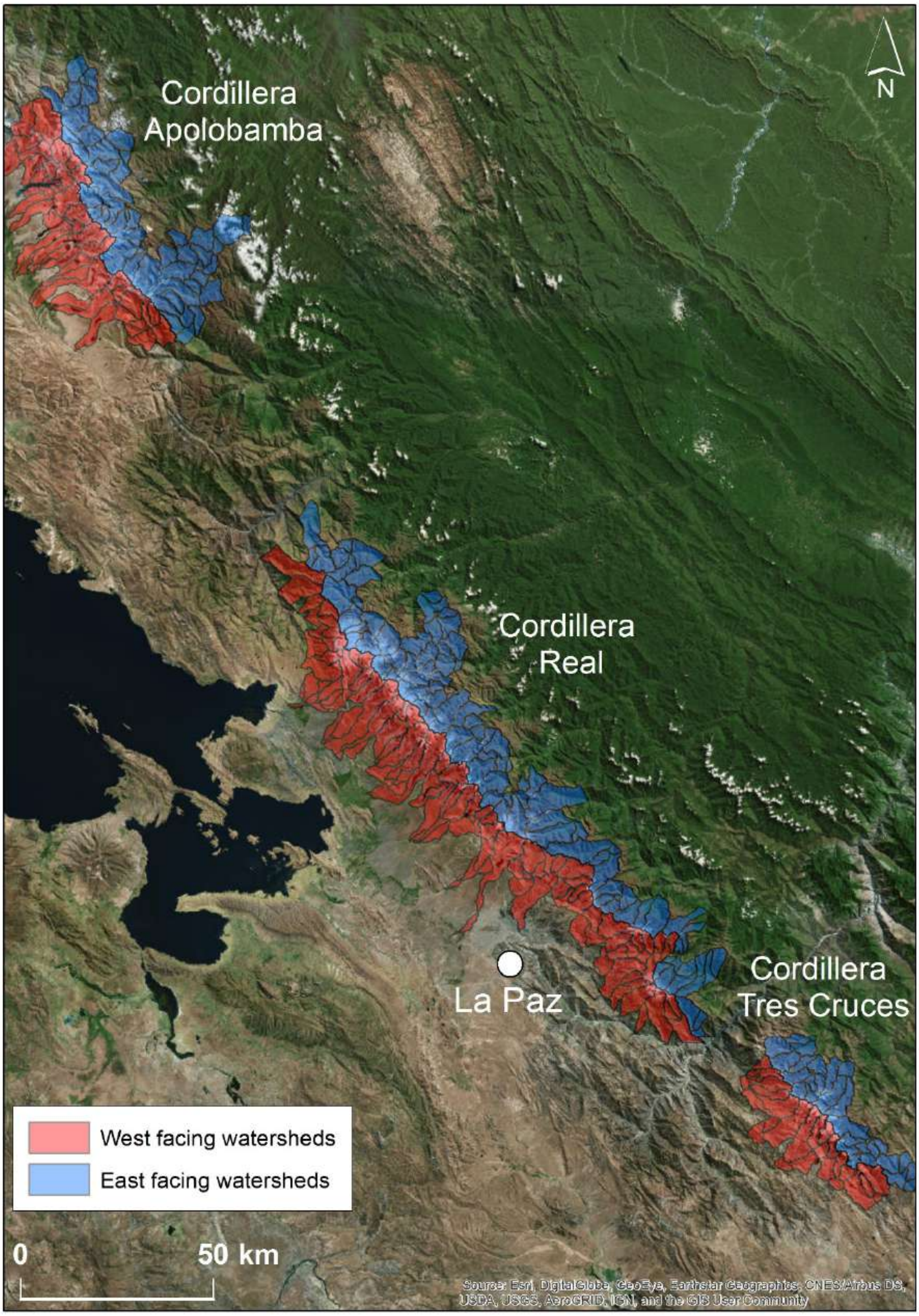
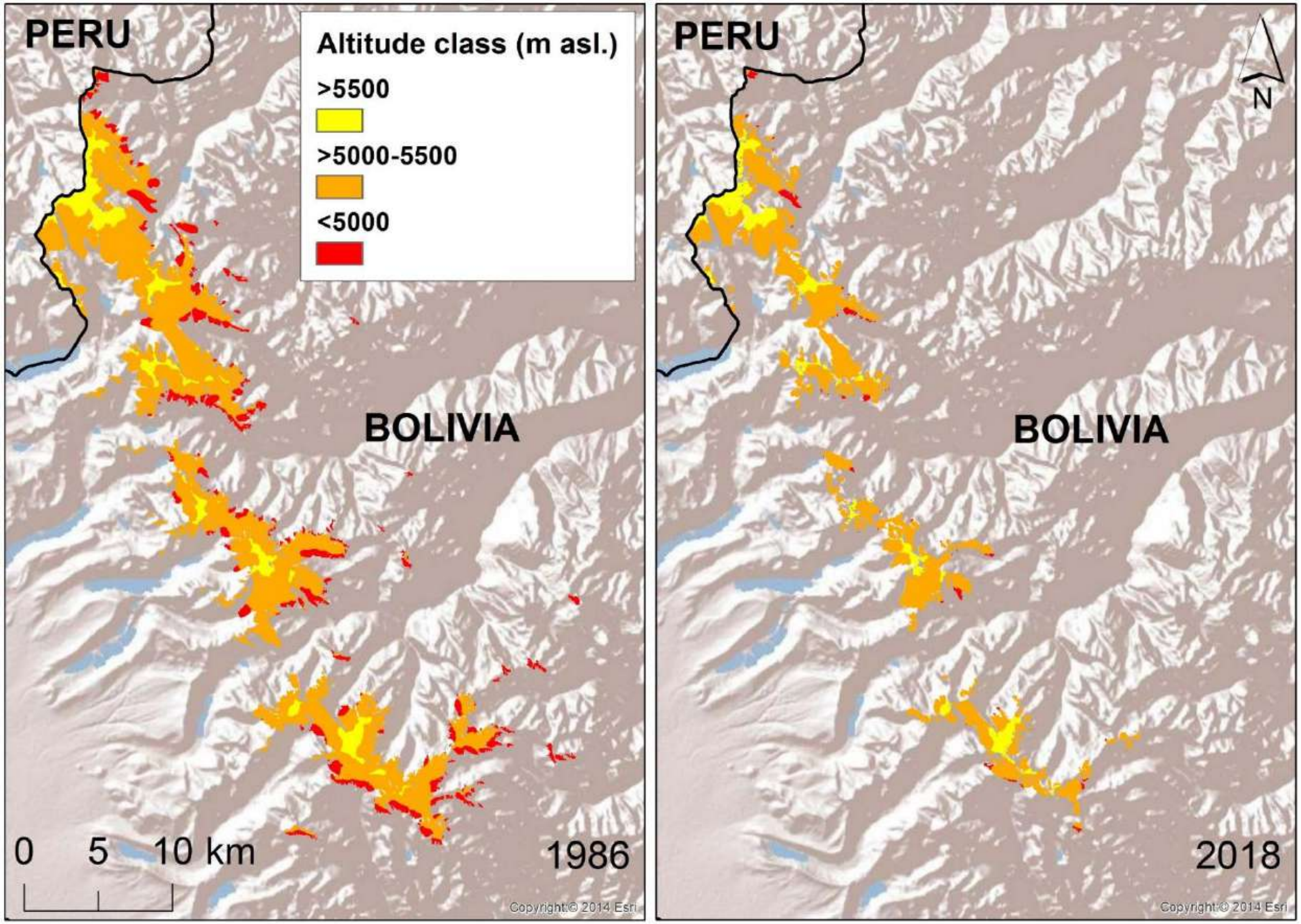
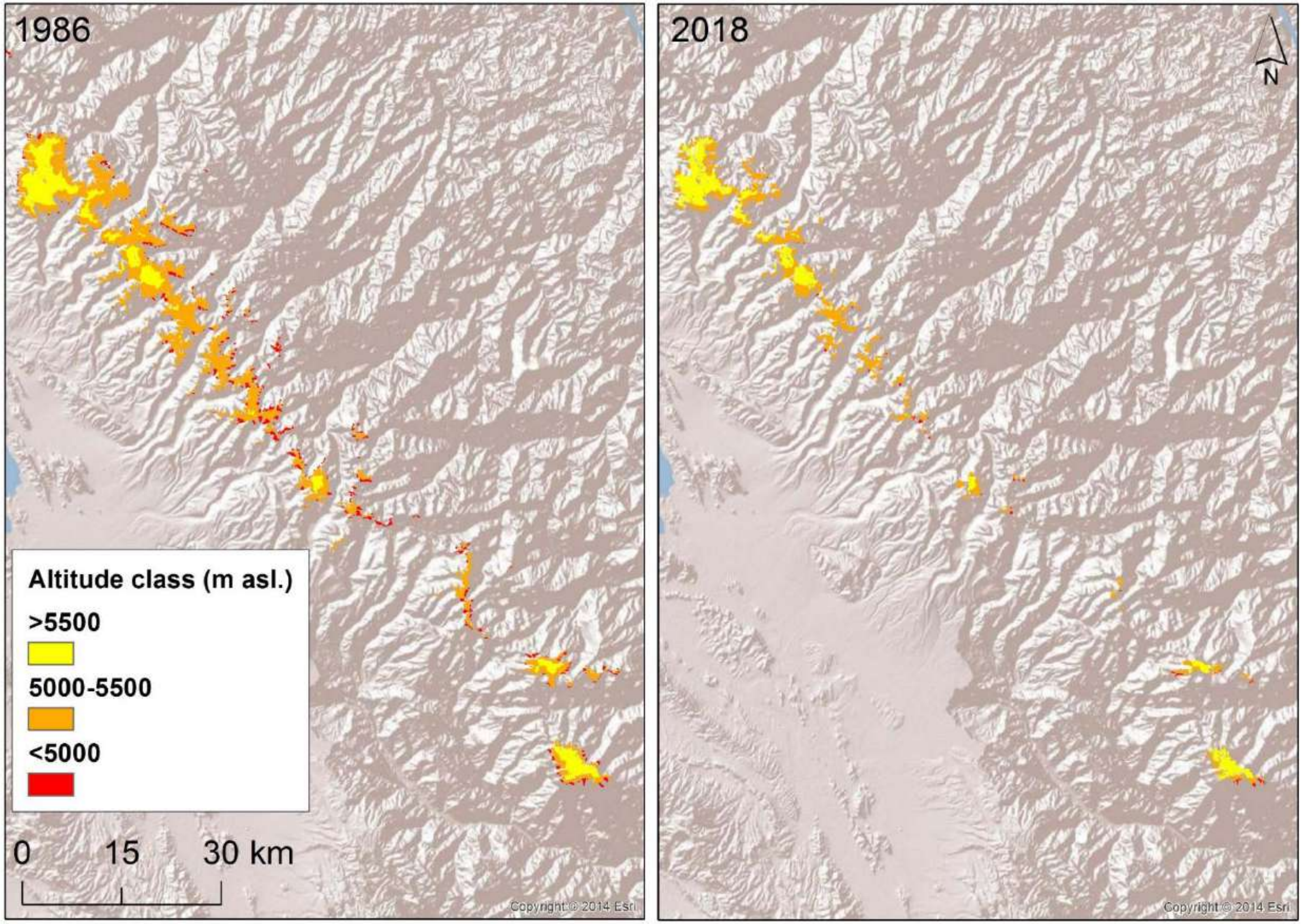


Fig. 3.1. Map illustrating the range divide in the Bolivian Cordillera Oriental.


PERU
Altitude class (m asl.)
>5500
>5000-5500
<5000
BOLIVIA
0 5 10 km
1986
Copyright © 2014 Esri
PERU
N
BOLIVIA
2018
Copyright © 2014 Esri


1986
2018
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>5500
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<5000
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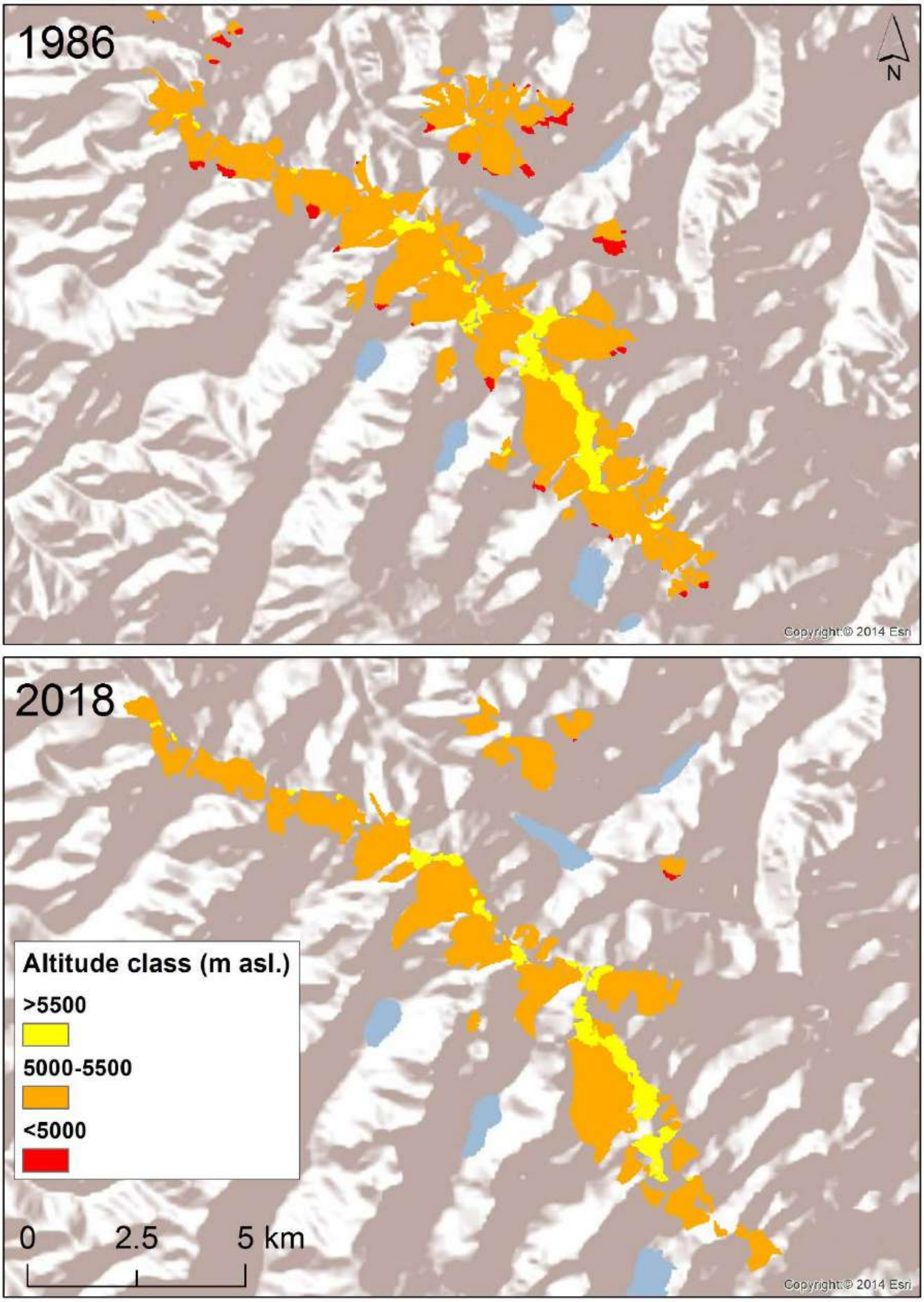


Fig. 3.2. Maps illustrating the altitude divisions on glaciers of the Cordillera Oriental between 1986 and 2018. Top: Cordillera Apolobamba, Middle: Cordillera Real, Bottom: Cordillera Tres Cruces.

3.2.3 Modelling ice-thickness for potential future lake development (2018 - onwards)

Ice thicknesses was obtained through use of the GlabTop basal shear stress inversion technique (Linsbauer et al., 2012; Paul and Linsbauer, 2012). GlabTop derives distributed ice thicknesses using Digital Elevation Models (DEMs) as a data input.

Here, the 2018 glacier outlines (generated as described in section 3.2.1) of all three glaciated ranges (Apolobamba, Real, Tres Cruces) in the Bolivian Cordillera Oriental were used.

The main Digital Elevation Model (DEM) used in this study is a version of the global Shuttle Radar Topographic Mission (SRTM) 1° provided by the Alaska Satellite Facility (ASF), University of Alaska Fairbanks. This DEM has been distributed free-of-charge since 2015, and has been artefact- and void-corrected and up-scaled from 30m to 12.5 m spatial resolution (ASF, 2015; Drenkhan et al., 2018).

Thickness measurements for year 2018 were derived from the DEM data using the GlabTop approach (Linsbauer et al., 2012; Paul and Linsbauer, 2012). First, glacier flowlines were determined, which was achieved through manual digitisation. An updated version of the software, GlabTop 2, overcomes the need to digitise flowlines manually by applying the relation at randomly selected grid cells, hence expediting the analysis (Frey et al., 2014; Farinotti et al., 2017). However, the GlabTop 2 code did not work and therefore the first version of the model was used.

The basis of the GlabTop technique is to rearrange the basal shear stress equation to solve for ice thickness (*h*) (Eq.3.3) along the digitised flowlines:

$$h = \frac{\tau}{f \, \rho \, g \, \sin\alpha} \tag{3.3}$$

where τ is the basal shear stress (kPa), ρ is ice density (900 kg/m^3), g is gravitational acceleration (9.81 m/s^2), f is a shape factor (here set to 0.8, following Paul and Linsbauer, 2012), and α is the glacier surface slope (degrees).

Shear stress (τ) can vary widely, so Paul and Linsbauer (2012) recommend an equation for determining an appropriate value based on a glacier's elevation range (Δh) in km.

$$\tau = 0.005 + 1.598\Delta h - 0.435\Delta h^2 \tag{3.4}$$

Here, a different shear stress value is assigned to each glacier flowline using Eq.3.4, with values varying between 5 and 150 kPa.

Ideally, ice thickness results should be compared against ground-truthed data. The only Bolivian glacier for which such data exist (through the application of ground penetrating radar – GPR) is the Zongo Glacier, in the Huayna Potosi region (Cordillera Real) (Réveillet et al., 2015). Hence, results from the GlabTop model (with 2010 glacier outlines) for the Zongo Glacier were compared against GPR-derived data to assess the validity of model outputs (Fig. 3.3).

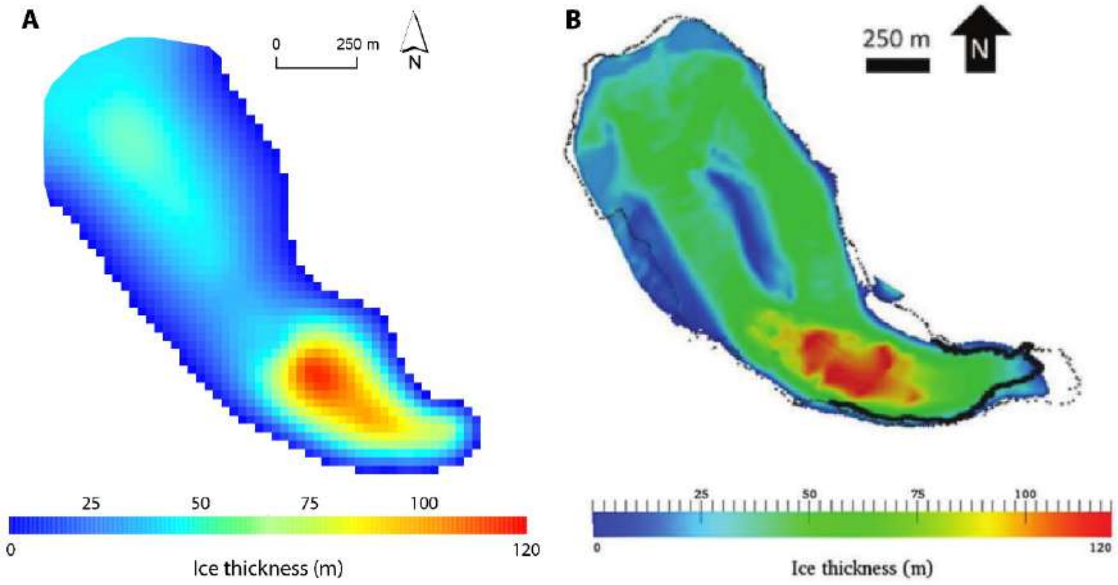


Fig. 3.3. Left: GlabTop method applied on Zongo glacier with the 2010 glacier outline. Right: GPR values obtained in 2010 by Réveillet et al. (2015). Right figure credit: Réveillet et al. (2015)

Moreover, recent research has attempted to estimate future locations of glacial lake development (Frey et al., 2010; Haeberli et al., 2016; Colonia et al., 2017; Drenkhan et al., 2018). In particular, numerical models like GlabTop have been used to estimate ice thickness and to identify locations of subglacial overdeepenings where water may pond following glacier recession. There is some known uncertainties to GlabTop modelling; the model tends to wrongly extract large overdeepenings under the glacier terminus due to the gap between the lowermost end of the branch line (suggested to be positioned 100 m away from the glacier terminus) and the 0 m ice thickness of the terminus itself (Frey et al., 2014; Drenkhan et al., 2018). To strengthen confidence in bed topographic modelling, an approach combining morphological criteria of the glacier surface and GlabTop was used here, similar to the approach applied by Frey et al. (2010) in the Swiss Alps and Colonia et al. (2017) and Drenkhan et al. (2018) in the Peruvian Andes.

The potential future lake extraction process was performed in three steps:

1. Glaciers with average surface slopes <5° and areas >2500 m^2 were mapped from the DEM. Numerous studies (e.g. Frey et al., 2010; Colonia et al., 2017; Drenkhan et al., 2018) have used this rapid method for pre-selection of sites with potential bed overdeepenings in large regions.
2. Google Earth, Bing Maps GIS Basemap and SPOT 6/7 imagery obtained from the European Space Agency (ESA) were used for visual interpretation of three morphological criteria of the glacier surfaces; i) increasing slope in flow direction, ii) onset of crevasse formation at the down-flow end of crevasse-free areas, and iii) lateral narrowing in the flow direction.
3. Finally, the results from steps 1 and 2 were compared to the results from the GlabTop bed topography extraction model.

After excluding sites from step 1, the analysis of morphological indicators took place on the remaining sites (Step 2). If at least two out of three criteria were met for each location in Step 2, then these sites were selected for potential lake formation and were compared with the GlabTop bed topography model extraction results (Step 3). All steps are illustrated in Fig. 3.4.

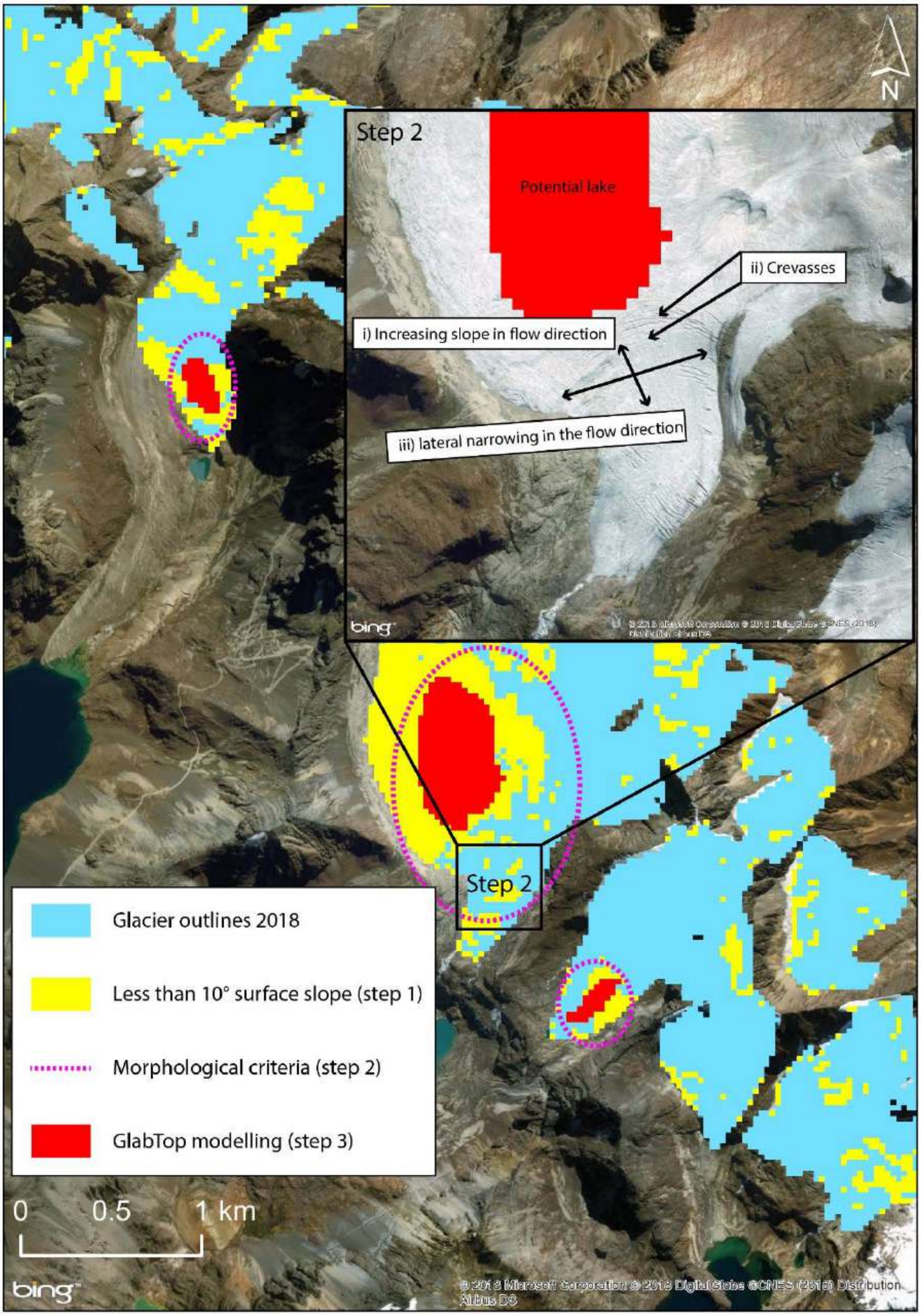


Fig. 3.4. Comparison of results from steps 1, 2 and 3 with the 2018 glacier outlines in a selected area in the Cordillera Tres Cruces. Mapping method following Frey et al. (2010), Colonia et al. (2017) and Drenkhan et al. (2018).

Bed topography was extracted for 2018 glaciers using GlabTop. A first-order estimation of the volume of potential future lakes was performed using the same depth-area relationship as Cook et al. (2016) for the Bolivian Cordillera Oriental (see section 3.2.1).

3.2.4 Qualitative hazard assessment of potential future lakes

In this study, a qualitative hazard assessment of potential future lakes is made using a number of the key GLOF risk assessment criteria collated in Chapter 4 (Kougkoulos et al., 2018a). Not all 13 of these criteria can be evaluated here given that the lakes have not yet formed. Specifically, three criteria can be evaluated, as shown in Table 3.2.

Table 3.2. Hazard criteria selected for the potential future lake evaluation (from Kougkoulos et al., 2018a).

Criterion	Unit	Low	Medium	High
Lake volume	$m^3 * 10^6$	$<1 * 10^6$	$1 * 10^6$ - $10 * 10^6$	$>10 * 10^6$
Steepest slope surrounding lake	degrees°	<30	30-45	>45
Distance between lake and steepest slope	m	500-250	250-10	10-contact

The first criterion in Table 3.2 is lake volume, which is estimated through application of an area-depth relationship developed by Cook and Quincey (2015), and which has been used in other studies (e.g. Cook et al., 2016; Kapitsa et al., 2017; Rounce et al., 2017b; Kougkoulos et al., 2018a, 2018b; Wilson et al., 2018).

The second criterion, focusing on the steepest slope surrounding the lake, is determined here using the bed topography without glaciers as extracted with GlabTop instead of using the current topography as observed in Google Earth. After the bed topography extraction, the steepest slope surrounding the lake is calculated from the resultant raster.

The third criterion, which focuses on distance between lake and steepest slope, is measured manually between the limits of the potential future lake and the pixels obtaining the steepest slope from the previous criterion.

Criteria 2 and 3 will be determined in order to estimate whether any rockfalls or avalanches could impact the lake. All criteria are scored as 1 (low hazard), 2 (medium hazard), 3 (high hazard) hazard, giving a combined lake score of between 3 and 9 (for all three criteria).

3.2.5 Monte Carlo Least Cost Path (MC-LCP) model

The Monte Carlo Least Cost Path (MC-LCP) model (Watson et al., 2015) was employed to provide a first-pass assessment of GLOF inundation from potential future lakes. MC-LCP produces least cost paths on all given pixels in a DEM that can be inundated downstream of a lake. It uses Monte-Carlo iterations to demonstrate the likelihood for each pixel downstream of the lake to be inundated (inundation frequency). Here, MC-LCP was employed to model future GLOFs since it is free of charge, works directly in any GIS and has been used successfully in previous studies (e.g. Watson et al., 2015; Rounce et al., 2016, 2017; Byers et al., 2018). Significant advantages of the model include its capacity to consistently represent potential flood propagation without the necessity to use a hydrologically correct DEM, making it more adaptable for high relief catchments where artefacts are more likely in global DEM products like the SRTM used in this study (Pitman et al., 2013; Watson et al., 2015). Potential floods were simulated with 100 iterations and a probability was assigned to each pixel. Since, in the context of potential future lakes, assumptions around the magnitude of the flood or the outburst susceptibility would be highly uncertain, sensitivity analysis was performed according to two scenarios:

1) Optimistic scenario: pixels with high inundation frequency (11 to 100 iterations) and therefore highly likely to be inundated in case of a small-medium event.
2) Pessimistic scenario: pixels with low inundation frequency (1-10 iterations) and therefore only inundated in case of an extreme event.

According to Watson et al. (2015), MC-LCP scenarios using the SRTM DEM produce more consistent flood characteristics than other open-source DEMs (e.g. ASTER GDEM), and therefore SRTM was preferred in this study for flood modelling.

3.2.6 Population, infrastructure data and potential impacts

Following similar methodology to Kougkoulos et al. (2018b), population and infrastructure data are required to assess potential GLOF impacts. These data were acquired from the GeoBolivia portal (http://geo.gob.bo/portal/), which offers open access to the 2012 population census and infrastructure data of the Bolivian National Statistical Institute. To quantify the downstream impacts, the number of buildings affected by the potential future flood were manually counted. For each community, the total population was divided by the number of buildings to estimate the number of people per building. This enabled an estimate of the number of people impacted by the flood. In order to rank the classes of risk by affected population, thresholds set by the EM-DAT/Emergency Events Database and Omelicheva (2011): specifically, <10 people (low impact/qualitative score 1), 10-1000 people (medium impact/qualitative score 2) and >1000 people (high impact/qualitative score 3). The qualitative hazard assessment discussed in section 3.3.2 is combined with this impact assessment in order to give a final risk score per lake, which is presented in the form of a matrix of hazard (likelihood) and consequence (impact) as X and Y axes, respectively.

3.3 Results

3.3.1 Glacier area changes and proglacial lake development in the Bolivian Andes (2014 - 2018)

Cook et al. (2016) reported 2014 glacier extent for the Bolivian Cordillera Oriental as 301.2 ± 30.1 km^2. Mapping undertaken in this study for 2018 reveals a total glaciated area of 280.1 ± 28.0 km^2 across the Bolivian Cordillera Oriental excluding the Peruvian glaciated areas, which represents a further shrinkage of ~20 km^2 since 2014. This equates to 6.7 % shrinkage in four years. Taken with the 1986 mapping results from Cook et al. (2016), shrinkage between 1986 and 2018 is 46.9 %. Fig. 3.5 illustrates glacier change that took place during these 32 years across all three mountain ranges integrating the results of this study and of Cook et al. (2016).

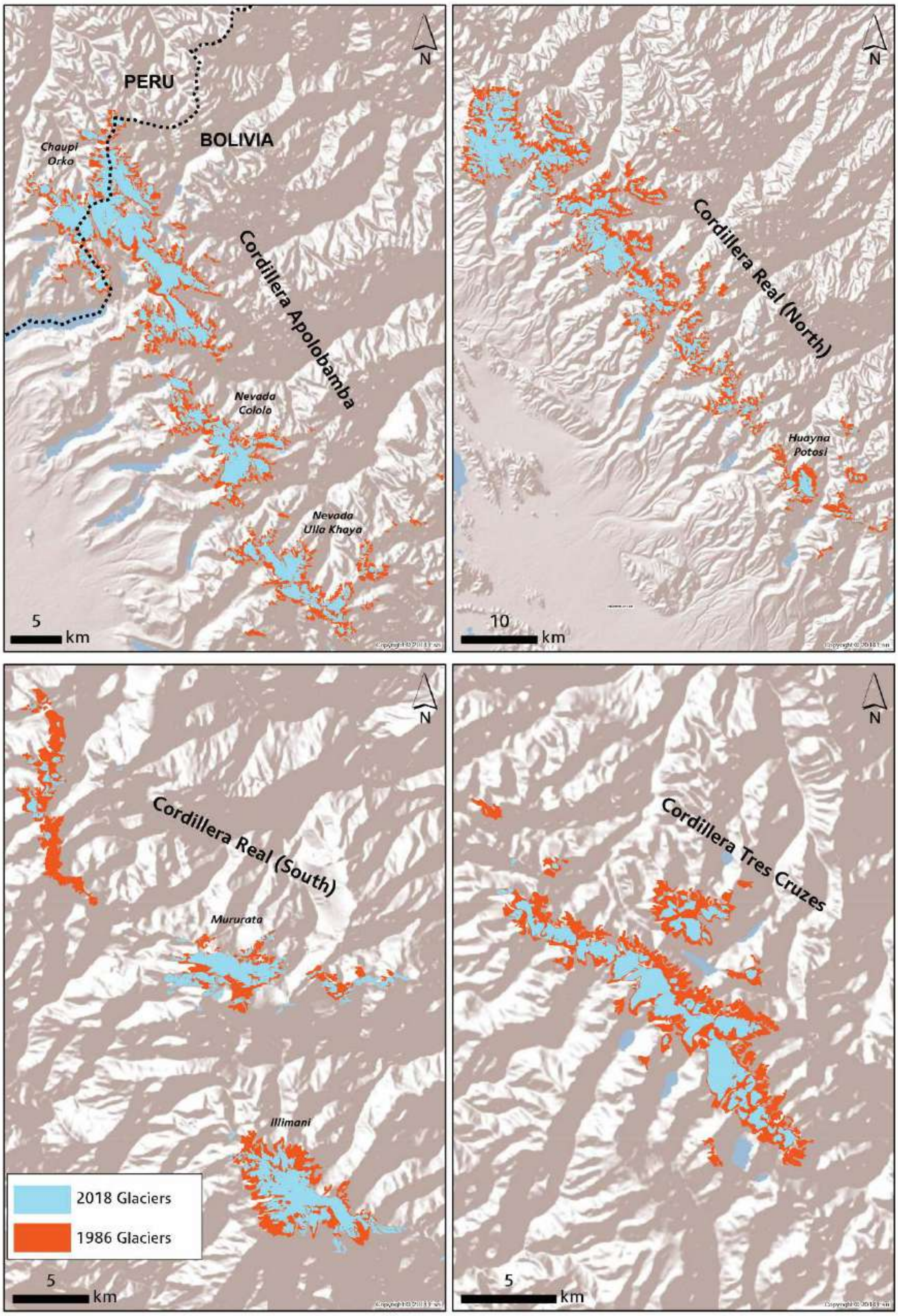
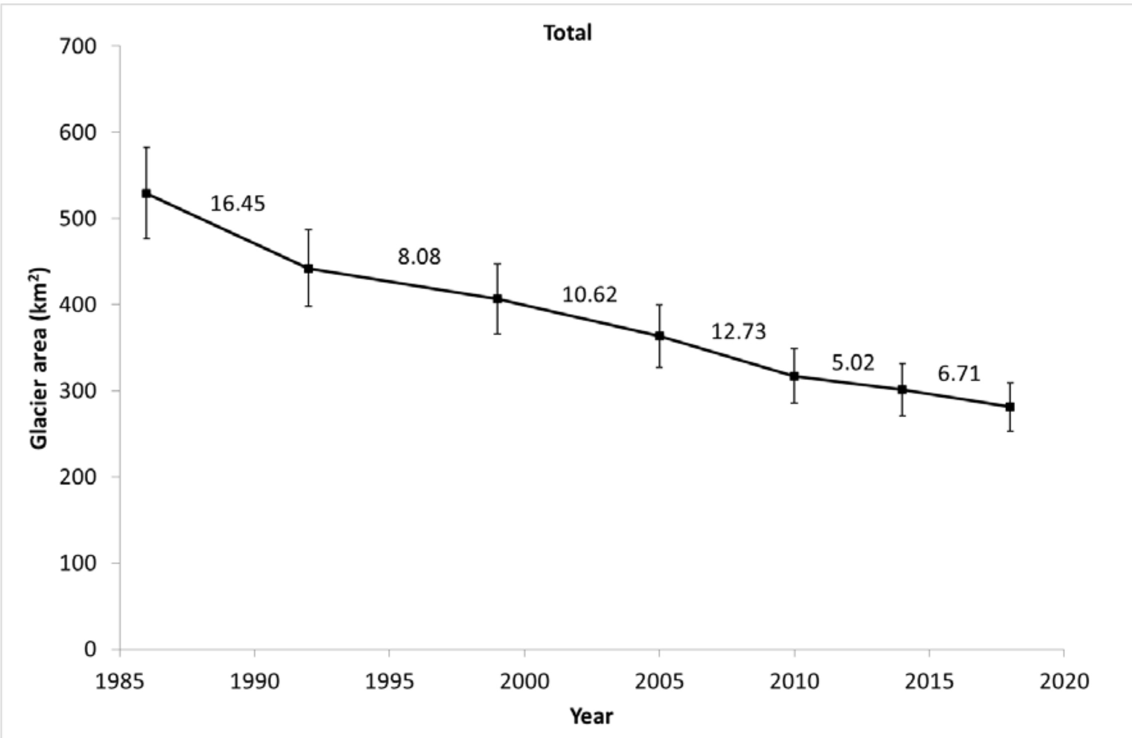


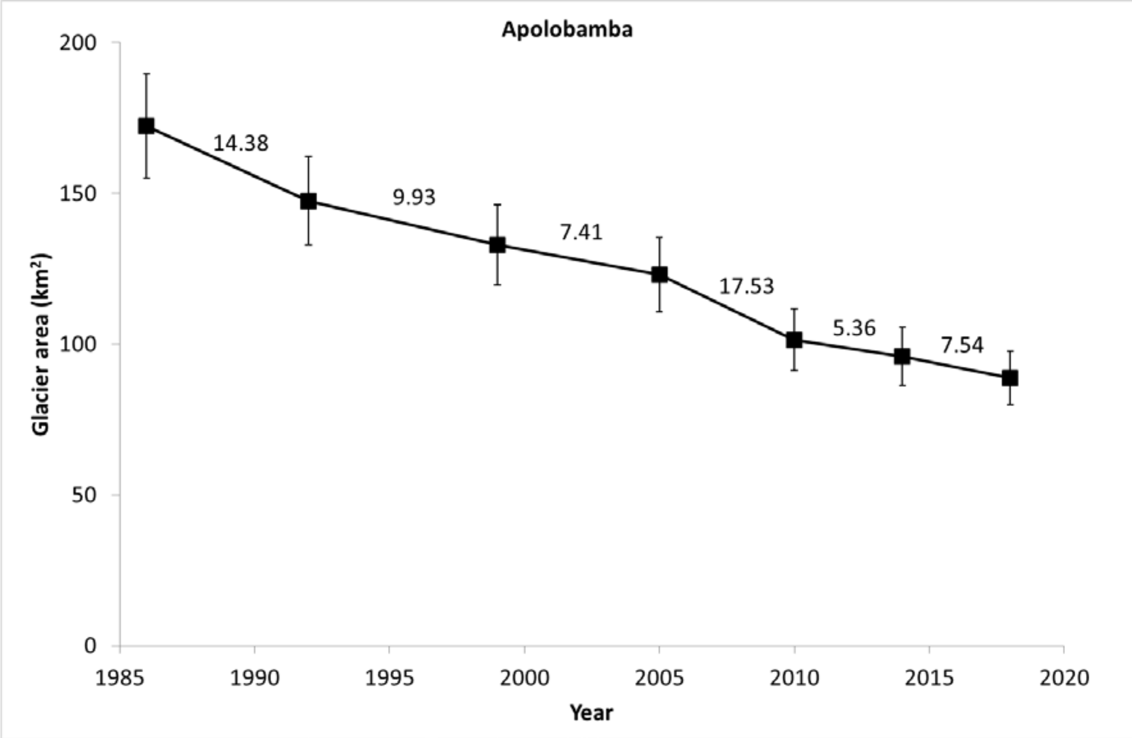
Fig. 3.5. Glaciated area changes in the three mountain ranges between 1986 and 2018. For mountain range locations in Bolivia see Fig. 1.1. For visibility purposes, only 1986 and 2018 areas are present on these maps. Base map is the Esri World Shaded Relief map (2014).

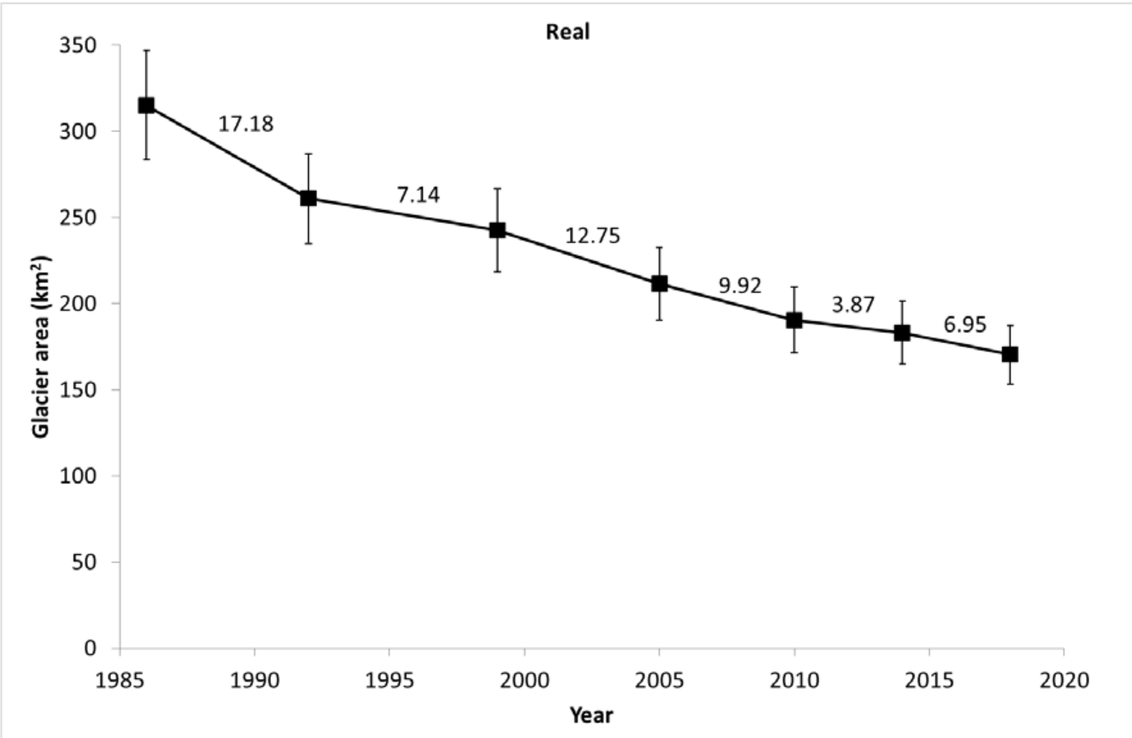
The greatest recent shrinkage (2014 - 2018) is observed in Cordillera Apolobamba, where there has been a 7.5 % area decline (from 96 ± 9.6 km^2 in 2014 to 88.9 ± 8.9 km^2 in 2018). In the Cordillera Real, glaciers have shrunk by 7 % from 183.1 ± 18.3 km^2 to 170 ± 17 km^2. The smallest shrinkage of all three glaciated mountain ranges was observed in the Cordillera Tres Cruces, from 22 ± 2.2 km^2 to 21.7 ± 2.2 km^2 (1.1 %).

Here, both the glacier area shrinkage rates (in %) per year as well as the absolute numbers of glacier areas losses per year (in km^2) are provided. It is important to highlight that when dividing between a) Cordilleras, b) west- and east-facing sides and c) altitudes, the shrinkage rates might sometimes be more important in one Cordillera (e.g. Cordillera Apolobamba) whereas the absolute numbers might show more important glacier area losses in another Cordillera (e.g. Real) as shown in the above paragraph. Therefore, results must be interpreted with caution.

These results are included in Fig. 3.6 alongside those of Cook et al. (2016) to provide a full suite of observations from 1986 to 2018.




Apolobamba
Glacier area (km²)
200
150
100
50
0
14.38
9.93
7.41
17.53
5.36
7.54
1985
1990
1995
2000
2005
2010
2015
2020
Year


Real
Glacier area (km²)
350
300
250
200
150
100
50
0
17.18
7.14
12.75
9.92
3.87
6.95
1985
1990
1995
2000
2005
2010
2015
2020
Year

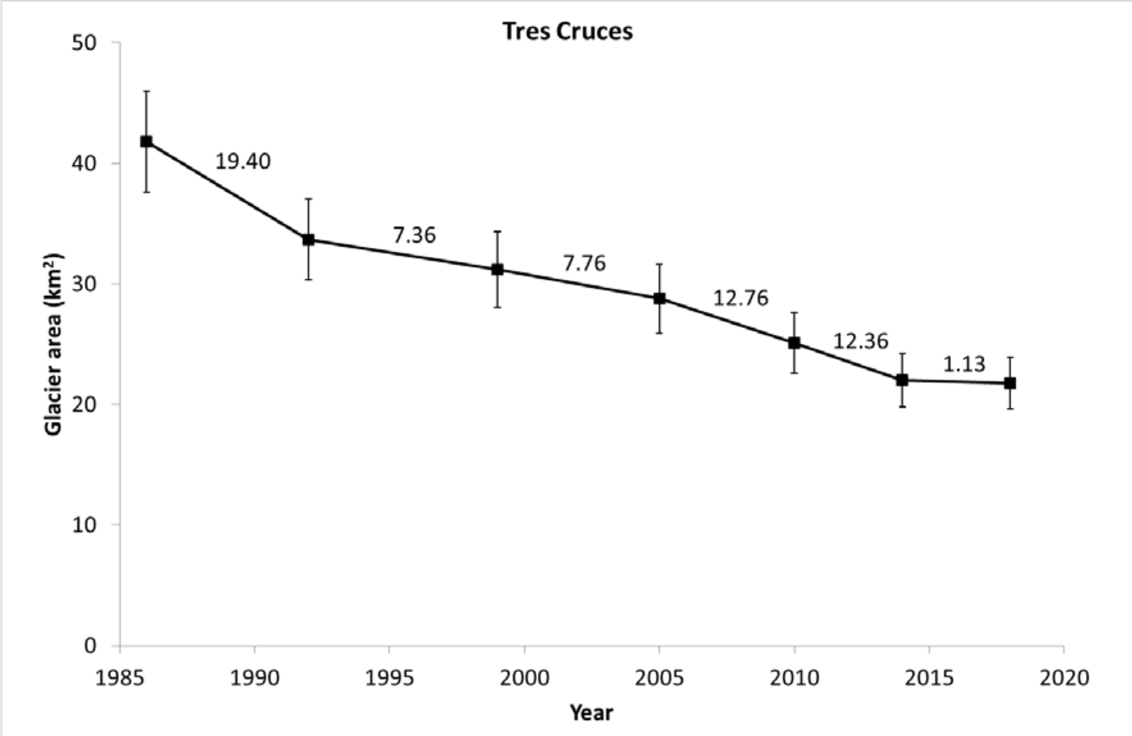
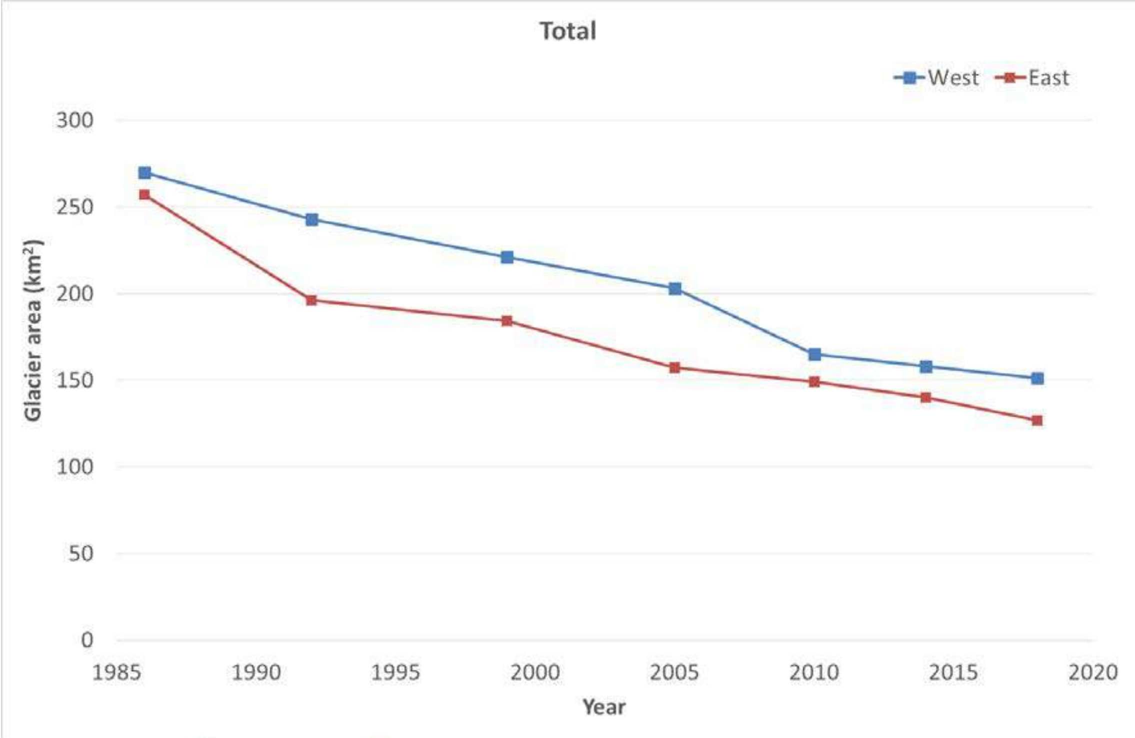


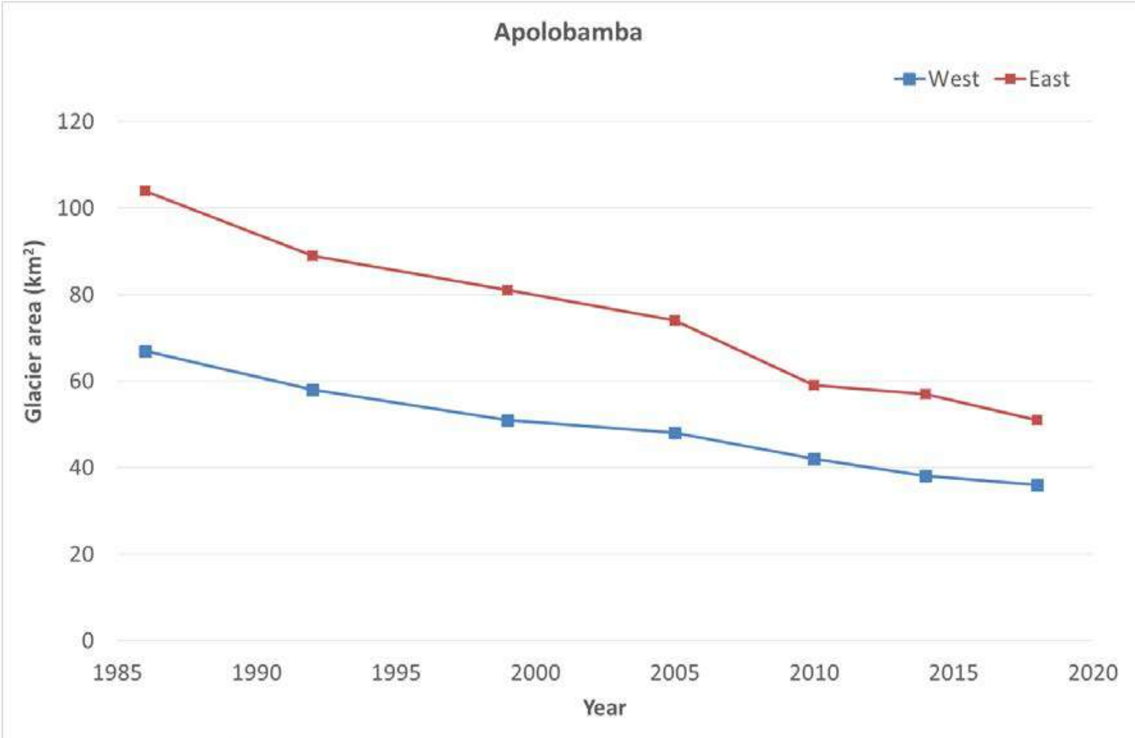
Fig. 3.6. Glacier area (km^2) and areal change (superimposed numbers on the graph in %) across the Bolivian Cordillera Oriental. Error bars are determined using Eq. (1) and represent an uncertainty of ± 10 %.

Previous studies have considered that GLOFs are likely when proglacial lakes are within 500m of a glacier (e.g. W. Wang et al., 2011; S. Wang et al., 2015; Cook et al., 2016). Both ice-contact lakes and lakes at a distance of <500m of a glacier could be impacted by mass movements, generating overtopping waves. This analysis reveals that four lakes have emerged (within 500 m from glacier margins) between 2014 and 2018, all of which are in the Cordillera Apolobamba but none were found to represent a GLOF risk to downstream communities or infrastructure.

3.3.1.1 Area change across the range divide

In total, during the 32-year study period (1986-2018), west-facing glacier areas shrunk from 396.91 km^{2}to 271.05 km^2, representing a 44 % loss; this is around 6 % less than east-facing glaciers, which shrunk from 258.28 km^2 in 1986 to 128.20 km^2 in 2018 (a loss of ~50 %). Nevertheless, these variations have been different in different years of study (Fig. 3.7). Concerning each Cordillera separately over the 1986-2018 observation period, the east-facing portion of the Cordillera Apolobamba shrunk from 104 km^2 to 51 km^2, representing 51 % shrinkage; this is an almost 5 % greater loss than the west-facing side (67 km^2 to 36 km^2, or 46 % shrinkage). The east-facing Cordillera Real shrunk from 136 km^2 to 69 km^2, or 49 % shrinkage, which is around 5 % greater loss than the west-facing side (179 km^2 to 101 km^2, or 44 %). Finally, the east-facing Cordillera Tres Cruces glaciers shrunk from 17 km^2 to 7 km^2, or 59 %, which is 17 % more than the west-facing side (24 km^2 to 14 km^2, or 42 % shrinkage) (Fig. 3.7). The east-facing Cordillera Real has known an increase in glacier area from 73 km^2 in 2005 to 82 km^2 in 2010, which lies within the 5 % mapping error (as described in section 3.2.1). Likewise, the east-facing Cordillera Tres Cruces experiences glacier area increase from 6 km^2 in 2014 to 7 km^2 in 2018 which could be due to accidental mapping of ice patches in the Landsat imagery.


Total
West
East
300
250
200
150
100
50
0
Glacier area (km^2)
1985
1990
1995
2000
2005
2010
2015
2020
Year


Apolobamba
West
East
120
100
80
60
40
20
0
Glacier area (km^2)
1985
1990
1995
2000
2005
2010
2015
2020
Year

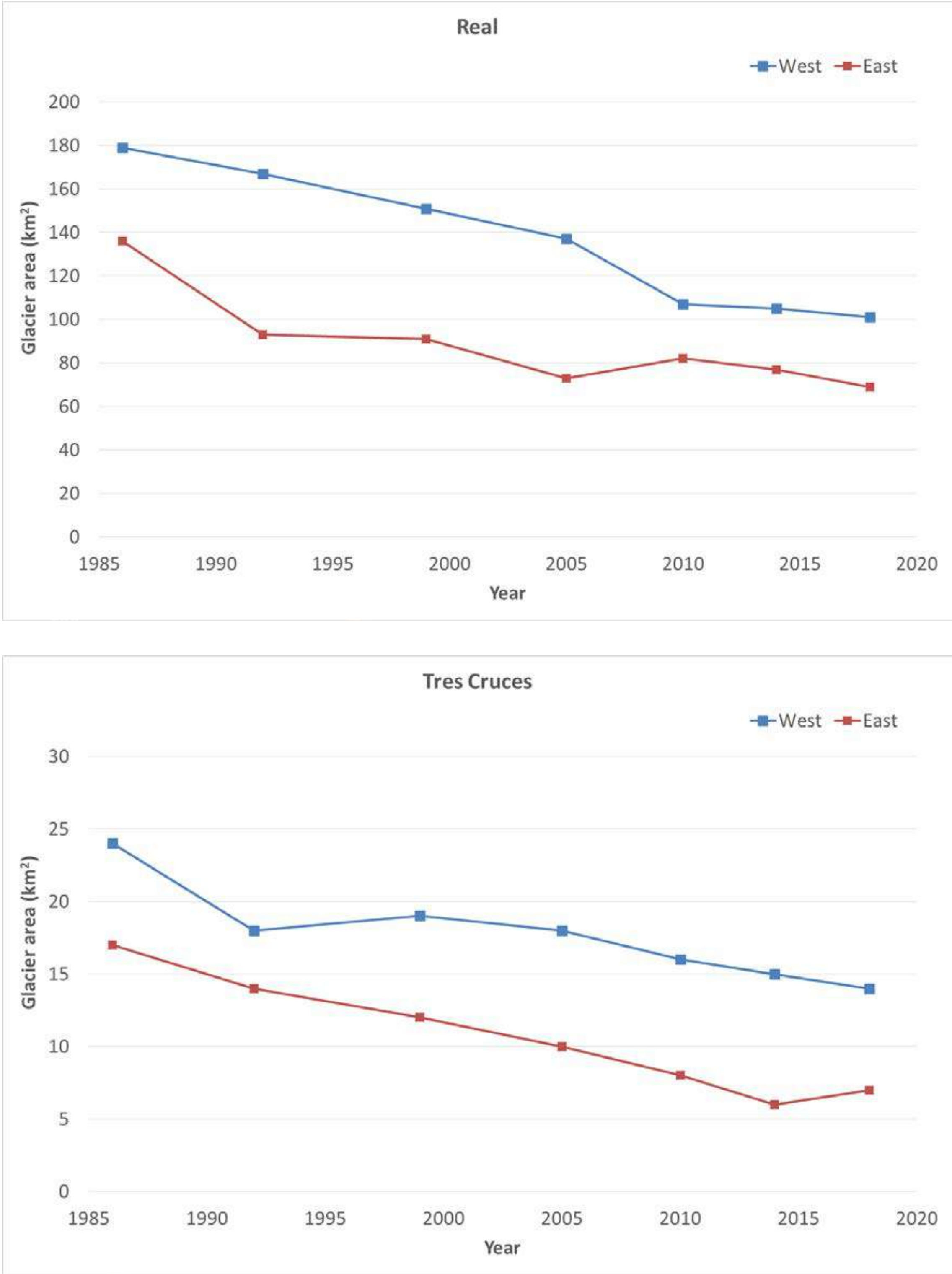


Fig. 3.7. Glacier area (km^2) between the west-facing and the east-facing basins across the Bolivian Cordillera Oriental

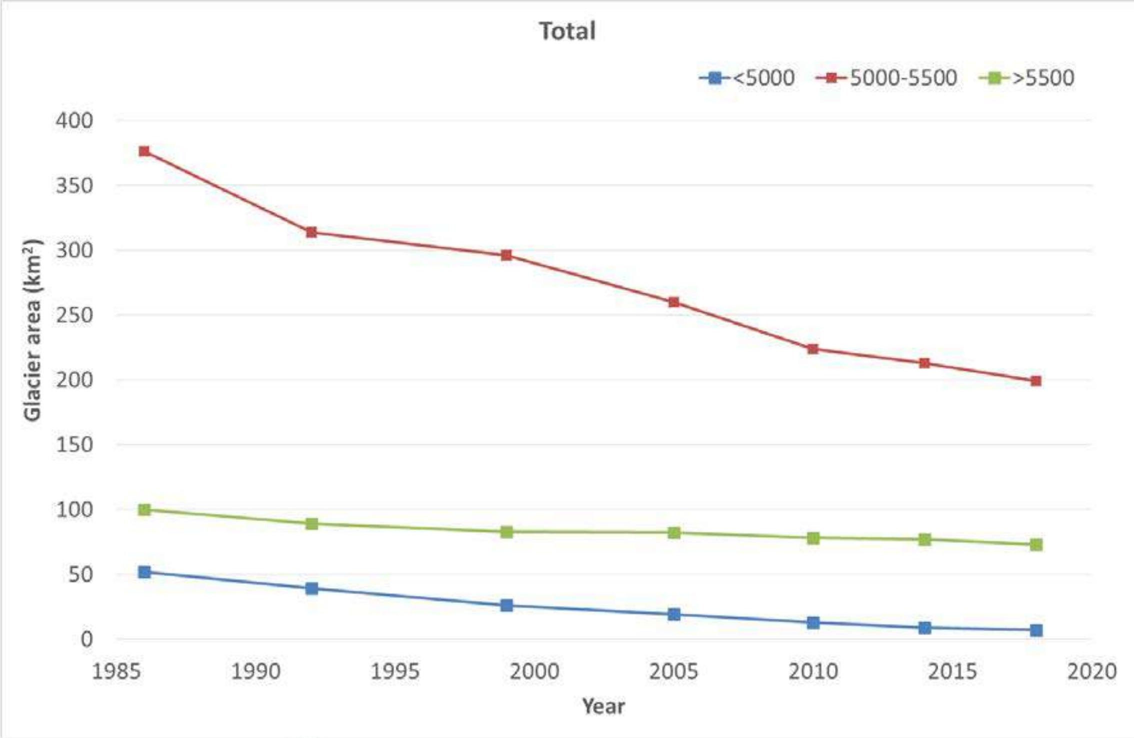
3.3.1.2 Area change with altitude

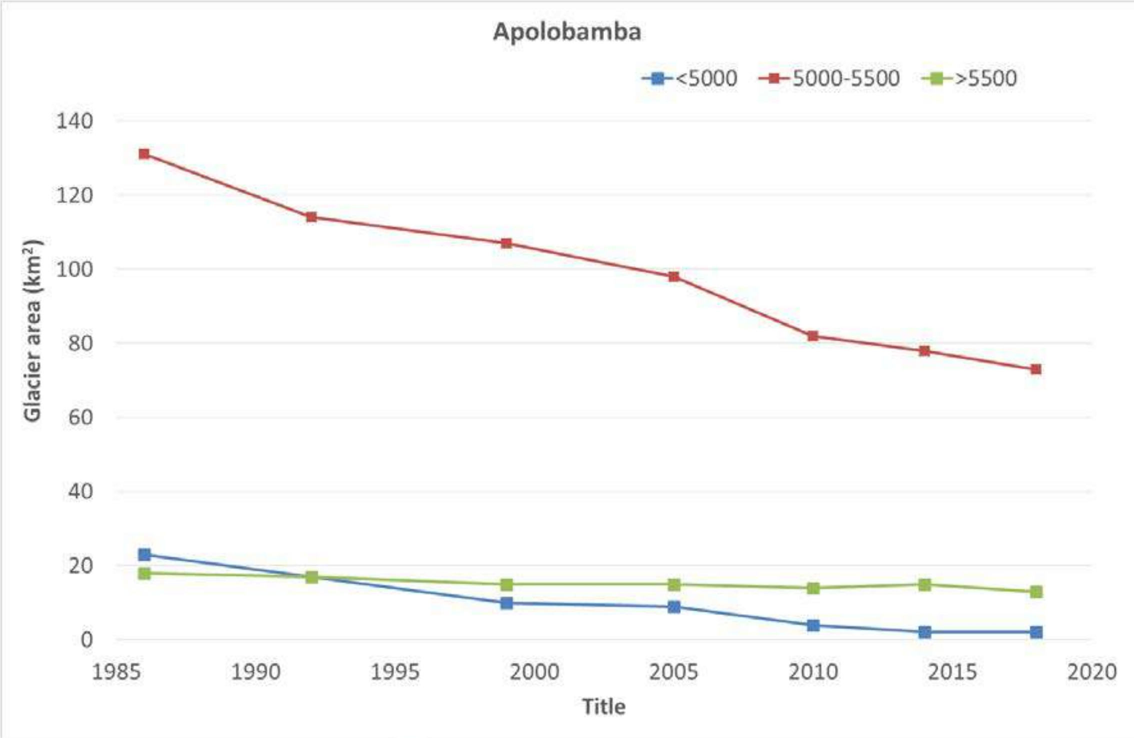
Unsurprisingly, over the 32 years of study, glaciers situated below 5000 m asl. elevation suffered the greatest proportional areal shrinkage (83 %) and only some ice patches remained by 2018 (7 km^2). Total glacier area between the 5000 and 5500 m asl. altitudes declined from 376 km^2 to 199 km^2 (or 47 %). Glaciers over 5500 m asl. have experienced the least change, declining in area from 100 km^2 to 73 km^2 (or 23 %).

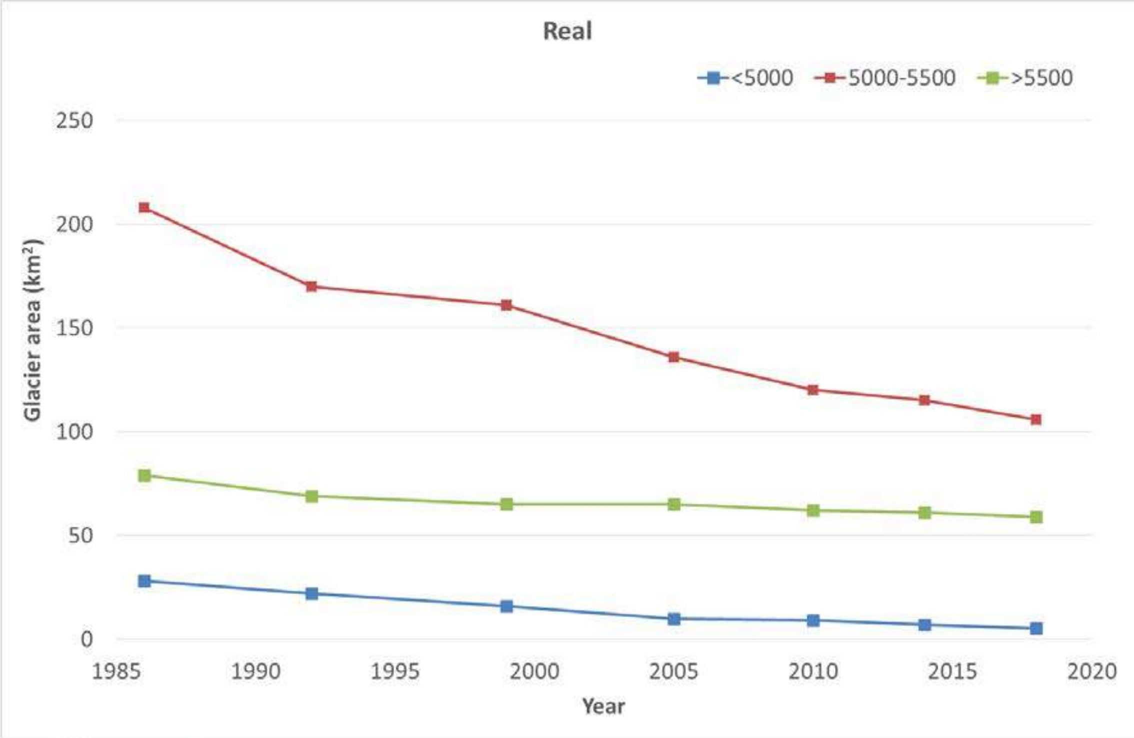
In detail, in the Cordillera Apolobamba, glaciers situated below 5000 m asl. shrunk from 23 km^2 to 2 km^2 (or 91 %); between 5000 and 5500 m asl. glaciers shrunk from 131 km^2 to 73 km^2 (or 44 %), and glaciers over 5500 m asl. declined from 18 km^2 to 13 km^2 (28 %).

In the Cordillera Real, glaciers situated under 5000 m asl. shrunk from 28 km^2 to 5 km^2 (82 %). Glaciers between 5000 and 5500 m asl. shrunk from 208 km^2 to 106 km^2 (or 49 %) and glaciers over 5500 m asl. declined from 79 km^2 to 59 km^2 (or 25 %).

In the Cordillera Tres Cruces, nearly all glaciers under 5000 m asl. had already entirely disappeared by 1986 (< 2 km^2). Glaciers between 5000 and 5500 m asl. shrunk from 37 km^2 to 20 km^2 (or 46 %). There are hardly any peaks exceeding 5500 m asl. in the Tres Cruces therefore the >5500 m asl. class is not represented in this Cordillera (Fig. 3.8).


Total
<5000
5000-5500
>5500
Glacier area (km²)
0
50
100
150
200
250
300
350
400
1985
1990
1995
2000
2005
2010
2015
2020
Year


Apolobamba
<5000
5000-5500
>5500
Glacier area (km²)
0
20
40
60
80
100
120
140
1985
1990
1995
2000
2005
2010
2015
2020
Title



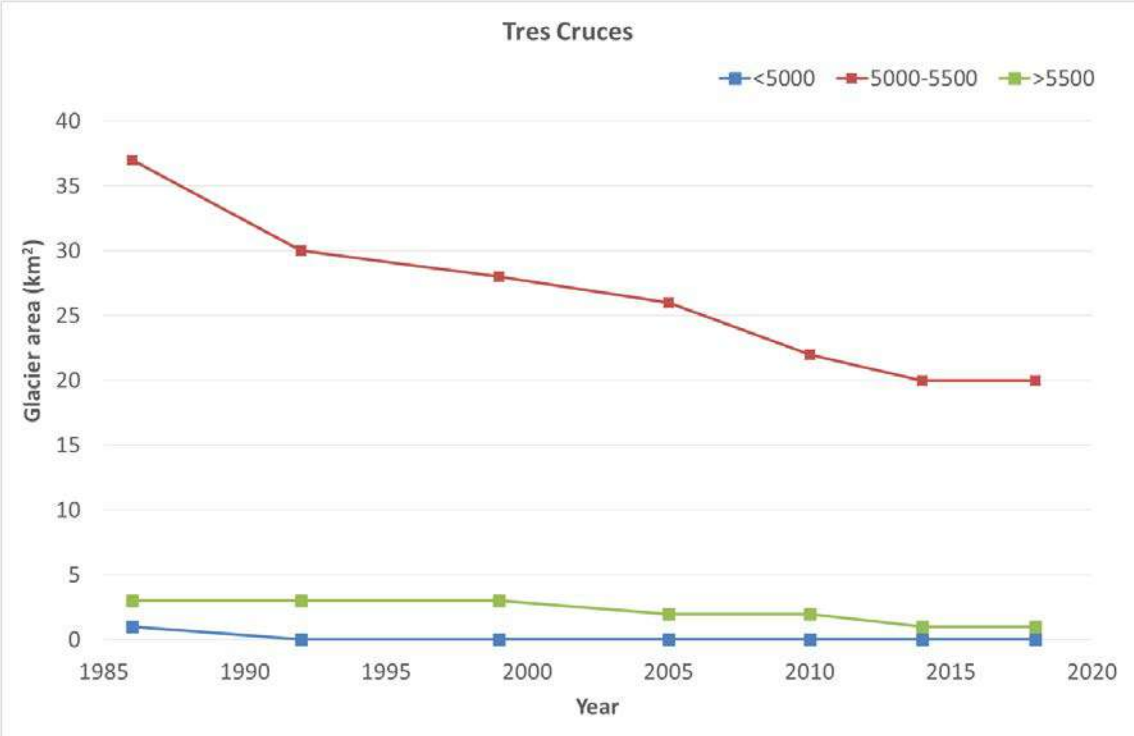


Fig. 3.8. Glacier area (km^2) between different altitudes (<5000 m asl.; 5000-5500 m asl.; >5500 m asl.) across the Bolivian Cordillera Oriental.

3.3.2 Future lake development (2018 - onwards)

Using the 2018 glacier outlines, 68 potential future lake locations are identified using the methods described in section 3.2.3. Some examples from the GlabTop modelling are illustrated in (Fig. 3.9). Potential future lake areas vary from ~0.01 km^2 to ~0.5 km^2. According to this method, most lakes could appear in the Cordillera Apolobamba, with 29 potential lake locations identified ranging in size from ~0.01 km^2 to ~0.5 km^2. In the Cordillera Real, 28 lakes could appear with sizes varying between ~0.01 km^2 and 0.15 km^2. Finally, in the Cordillera Tres Cruces, 11 lakes could appear, ranging in size from ~0.01 km^2 to ~0.3 km^2 (Fig. 3.9).

A first order approximation of the potential future lake volumes using the area-depth relationship described in section 3.2.1 illustrates that lakes in the Cordillera Apolobamba could hold between ~35,000 m^3 and ~15,194,130 m^3 of water. The total water volume could reach ~55,000,000 m^3. In the Cordillera Real, lake volumes could range from ~50,000 m^3 to ~2,728,296 m^3, with a total volume of ~12,000,000 m^3. Finally, in the Cordillera Tres Cruces, lake volumes could range from ~72,000 m^3 to ~7,186,704 m^3. The total volume of water from lakes in the Cordillera Tres Cruces could reach ~11,000,000 m^3.

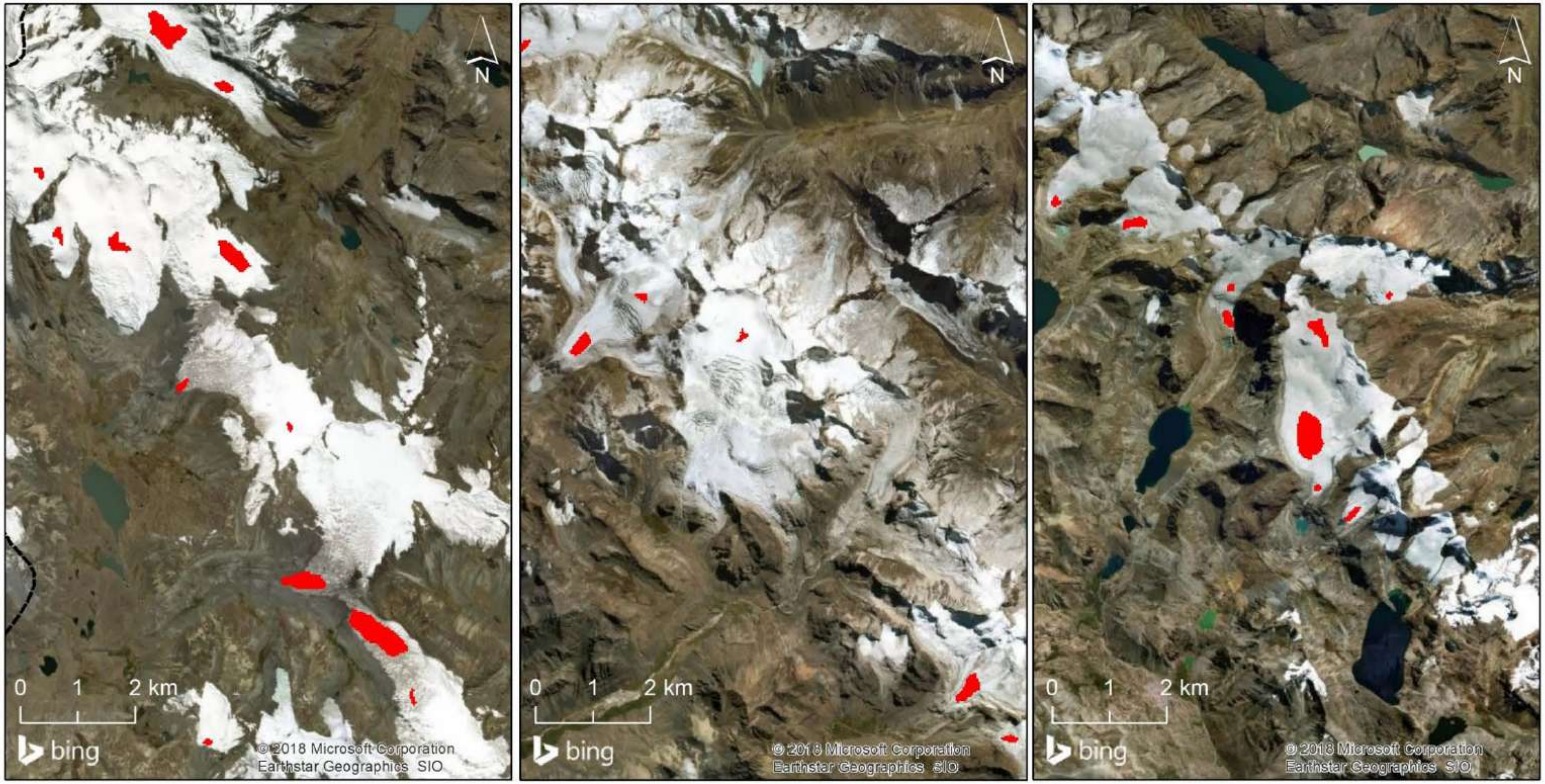


Fig. 3.9. Examples of overdeepenings (red) identified by GlabTop in the three Cordilleras of the Bolivian Andes. Left: Apolobamba, Centre: Real, Right: Tres Cruces.

3.3.3 Qualitative hazard assessment of potential future lakes

Concerning the 68 potential future lakes identified in the previous section (3.3.2), the same method used in Cook et al. (2016) for the identification of lakes that contain population downstream was used. In short, this was achieved using infrastructure data from GeoBolivia (http://geo.gob.bo/) and visually cross-referencing these data with Google Earth and Bing Maps. Lakes that have direct hydrological connection to downstream infrastructure and communities (e.g. where a road or village was in the direct path of a GLOF event), and possess infrastructure within 20 km downstream of the proglacial lakes were considered at risk (Cook et al., 2016) (Fig. 3.10). However, floods could propagate further than 20 km (Cook et al., 2016).

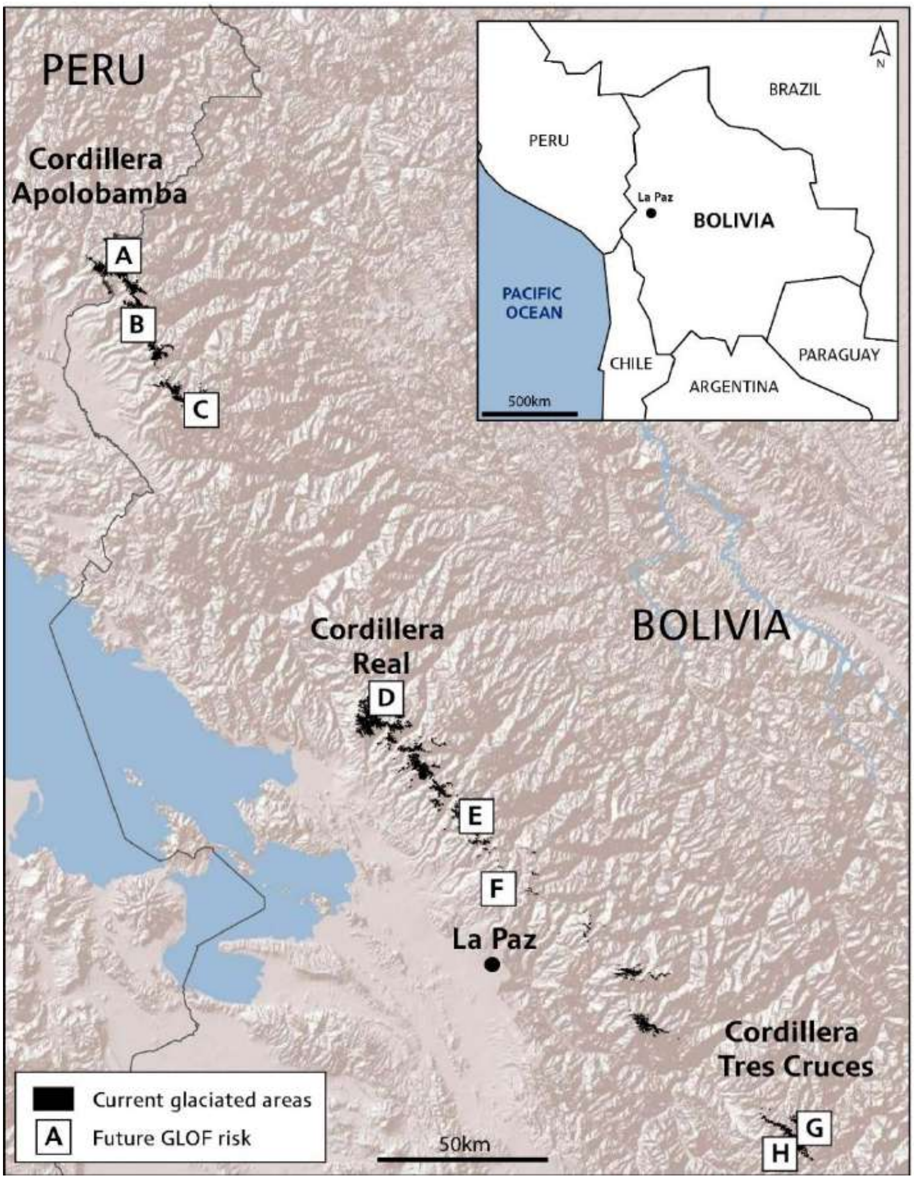


Fig. 3.10. Location of subglacial overdeepenings that could form lakes when glaciers recede and which possess population downstream.

In total, three lakes could appear in the Cordillera Apolobamba, three lakes in the Cordillera Real, and two lakes in the Cordillera Tres Cruces; there are 12 communities downstream from these locations (Fig. 3.10). The three lake locations (Fig. 3.11 - A, B, C) in the Cordillera Apolobamba could be a concern for four downstream communities in total. The potential overdeepening situated upstream from the community of Puina (Fig. 3.11 - A) is situated beneath steep glaciated slopes (>45°), which could become the source of ice avalanches into the lake, leading to a GLOF. Location B, situated upstream from Agua Blanca and Pelechuco village (which are also under threat from an already existing lake in proximity – see Kougkoulos et al., 2018a, 2018b), appears to be less vulnerable to avalanches or rockfalls since its location is far from any steep slopes. (Fig. 3.11 - B). Location C is situated upstream from the village of Quelwa Cota in the southernmost part of the Cordillera Apolobamba (Fig. 3.11 - C). The surrounding environment in proximity is not characterised by any steep slopes. Location D lies upstream from the village of Cooca in the northernmost part of the Cordillera Real (Fig. 3.12 - D). No steep slopes are in proximity of this potential lake location. Location E is also situated in the Cordillera Real upstream from the community of Umapalca. Surrounding slopes are relatively shallow (<30°) and are located further than 250 m from the potential future lake border (Fig. 3.12 - E). Location F is situated upstream from the community Campamento de la Union in the Cordillera Real (Fig. 3.12 - F). Steep glaciated slopes (>45°) in proximity <250 m could lead to avalanche or rockfall activity if this lake were to appear. Location G is found in the Cordillera Tres Cruces, upstream from three villages (Santa Roza, Molinos-Pongo and Quime) (Fig. 3.13 - G). Again, no steep slopes surround this potential lake location. Therefore, in the case an ice-dammed lake appears, continuous monitoring should take place before further glacier shrinkage leads to a GLOF. Location H also lies in the Cordillera Tres Cruces upstream from the communities of Rodeo and Bella Vista (Fig. 3.13 - H). The surroundings of the potential future lake location are <30° steepness and further than 250 m away, therefore not posing a high risk of avalanching from the glaciated slopes in proximity. Table 3.3 summarises the hazard criteria evaluation for each lake.

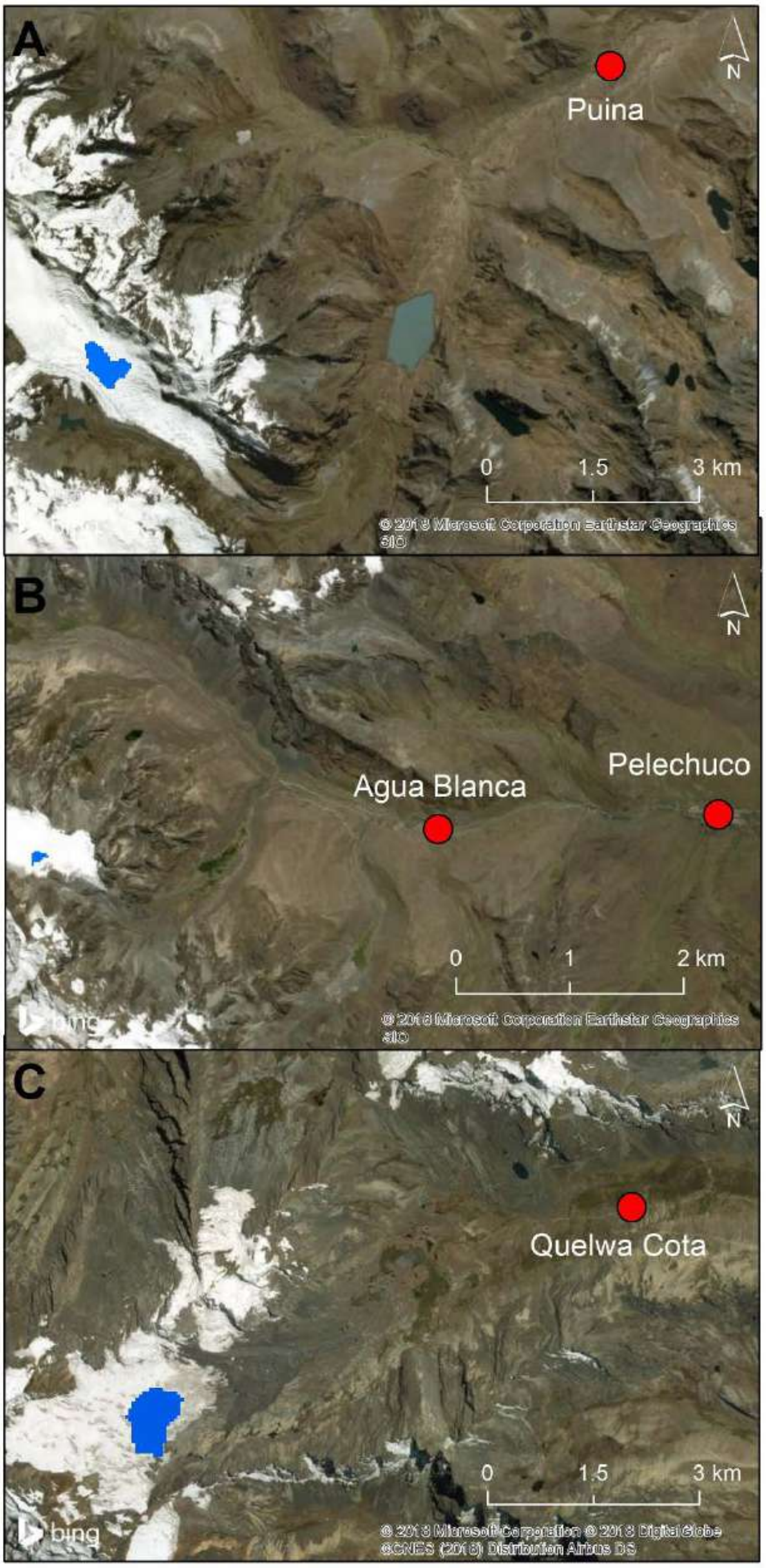


Fig. 3.11. Location of lakes A, B and C (blue polygons) and the communities potentially affected (red circles).

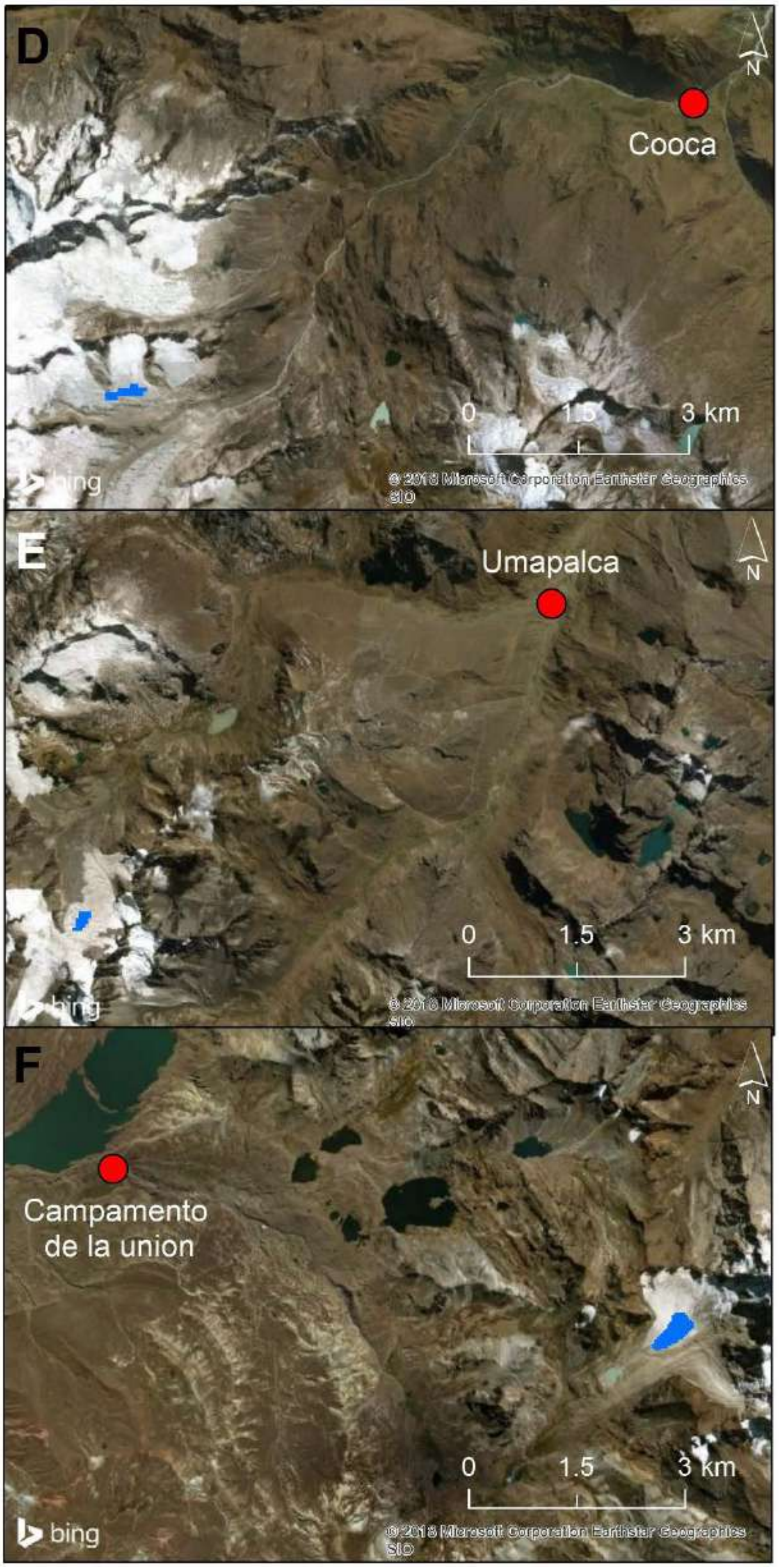


Fig. 3.12. Location of lakes D, E and F (blue polygons) and the communities potentially affected by future GLOFs (red circles).

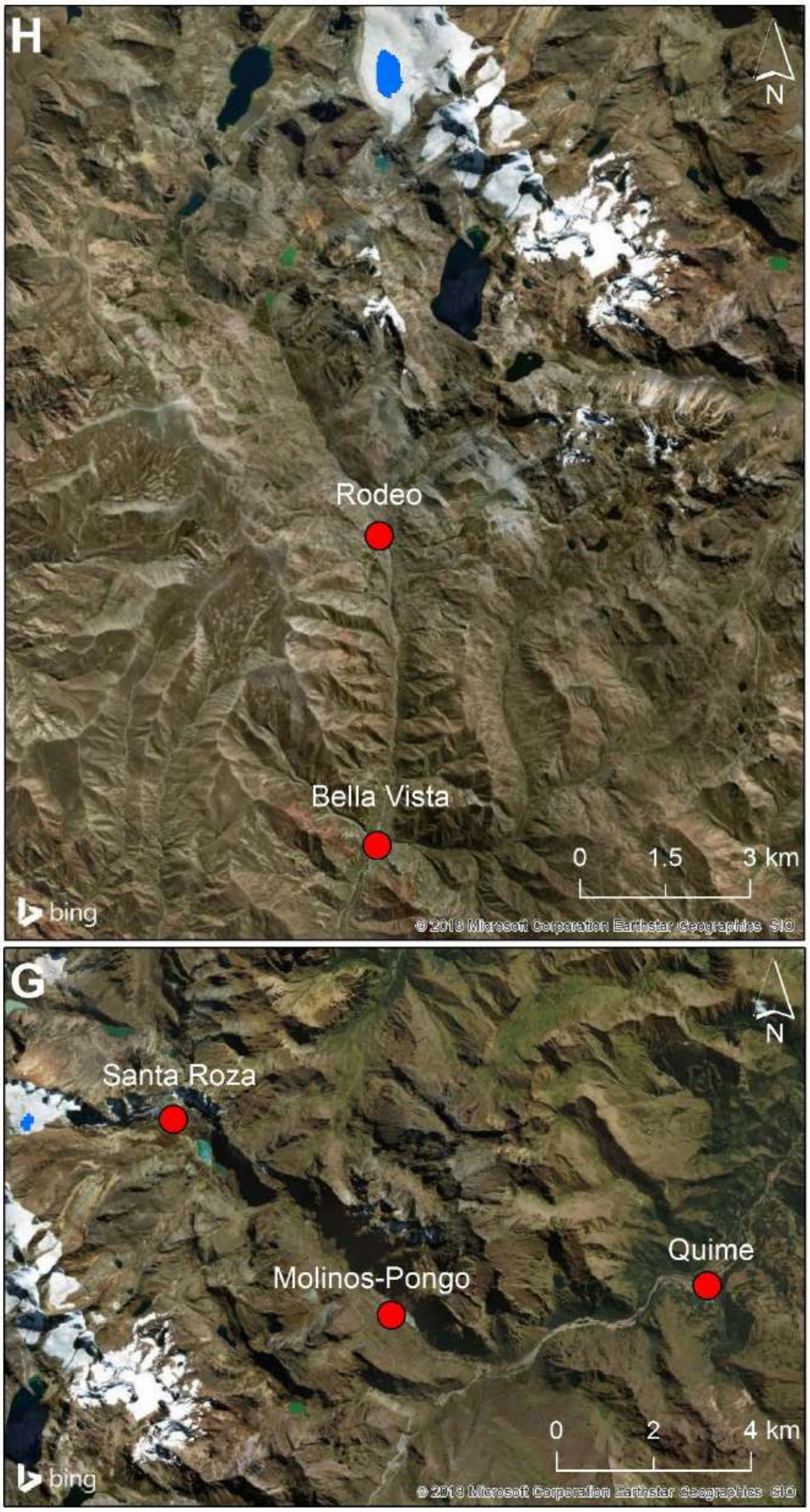


Fig. 3.13. Location of lakes H and G (blue polygons) and the communities potentially affected by future GLOFs (red circles).

Table 3.3. Evaluation of hazard criteria per potential future lake.

Potential lake	Cordillera	Potential lake coordinates (UTM)	Area (m^2)	Depth (m)	Volume (m^3)	Steepest slope surrounding lake (°)	Distance between lake and steepest slope (m)
A	Apolobamba	19 L 478977 8379255	232903	22	5123866	>45	220
B	Apolobamba	19 L 482645 8361023	26802	8	214416	<30	470
C	Apolobamba	19 L 498566 8339169	197782	20	3955640	<30	240
D	Real	19 L 552119 8249797	68517	13	890721	<30	360
E	Real	19 K 576357 8220741	42678	10	426780	<30	340
F	Real	19 K 588734 8200961	151572	18	2728296	>45	270
G	Tres Cruces	19 K 676071 8124915	69390	13	902070	<30	330
H	Tres Cruces	19 K 674640 8121348	299446	24	7186704	<30	490

3.3.4 Potential GLOF impact assessment

MC-LCP modelling results for communities in the Cordillera Apolobamba are presented in Fig. 3.14 (see also Table 3.4). Lake A could affect between 105 and 133 people in the village of Puina, depending on which scenario is considered. Lake B could affect a total population ranging from 298 to 688 people in Agua Blanca and Pelechuco. Finally, lake C only affects the community of Quelwa Cota in the pessimistic scenario, in which case 69 people are estimated to be affected.

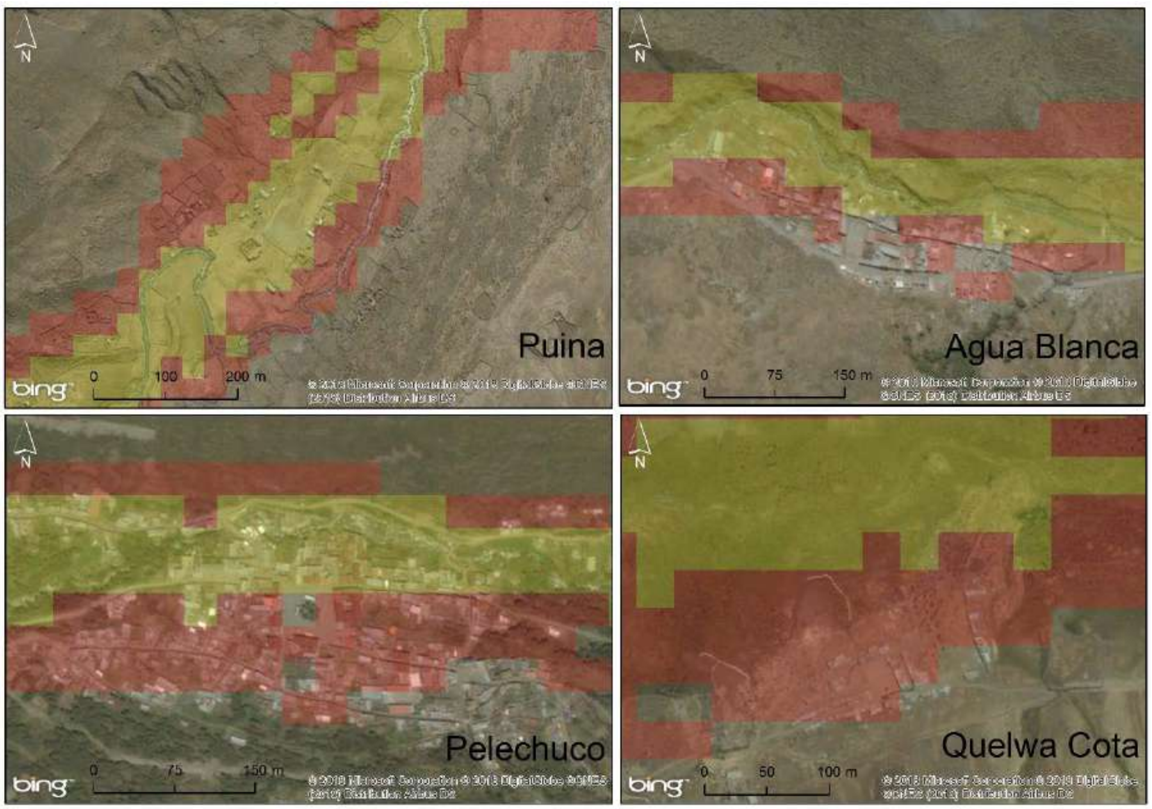


Fig. 3.14. GLOF impacts (from potential future lakes) on four communities in the Cordillera Apolobamba. Yellow=optimistic scenario. Red = pessimistic scenario.

In the community of Cooca, in the Cordillera Real, lake D could affect 227 people in the optimistic scenario, or 386 people in the pessimistic scenario (Fig. 3.15; Table 3.4). A GLOF from lake E could affect less than 10 people in the village of Umapalca for the optimistic scenario, rising to 50 for the pessimistic scenario. Finally, downstream from lake F, at the Campamento de la Union, between 10 and 39 people would be affected by a GLOF.

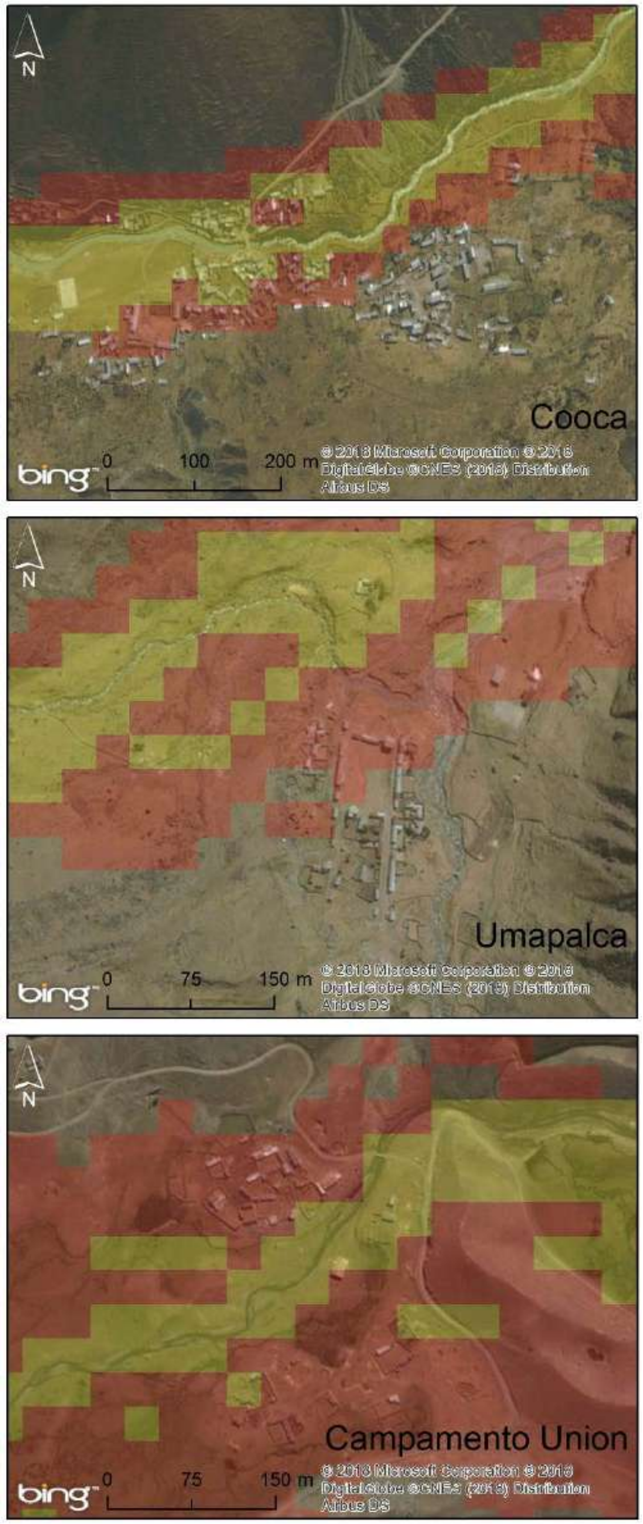


Fig. 3.15. GLOF impacts (from potential future lakes) on three communities in the Cordillera Real. Yellow=optimistic scenario. Red = pessimistic scenario.

In the Cordillera Tres Cruzes, lake G situated upstream from Santa Roza, Molinos-Pongo and Quime could affect between 255 and 1083 people if it were to burst (Fig. 3.16; Table 3.4). Lake H situated above the villages of Rodeo and Bella Vista would affect between 193 and 414 people.

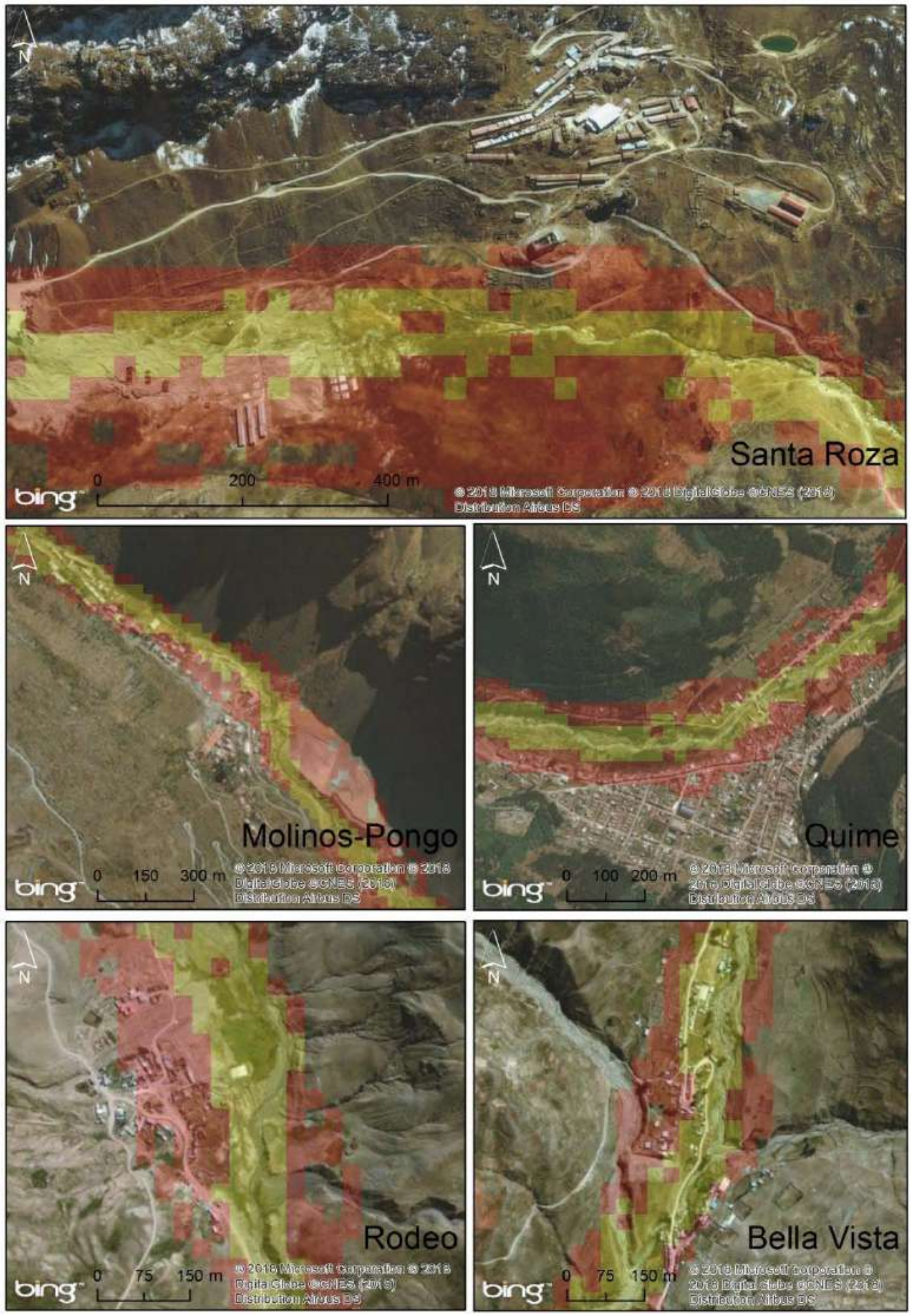


Fig. 3.16. GLOF impacts (from potential future lakes) on five communities in the Cordillera Tres Cruzes. Yellow=optimistic scenario. Red = pessimistic scenario.

Impacts on each community are shown in Table 3.4 considering both ‘optimistic’ and ‘pessimistic’ scenarios. If all lakes were to burst, a range of ~1100 to ~2860 people could be affected from flooding.

Table 3.4. Estimated number of buildings and population affected per community and per scenario (optimistic and pessimistic) in the event of hypothetical future floods.

Lake	Communities affected	Communities coordinates (UTM)	Number of buildings	Population	Buildings affected		Population affected	
					optimistic scenario	pessimistic scenario	optimistic scenario	pessimistic scenario
A	Puina	19 L 484079 8383824	81	244	35	44	105	133
B	Agua Blanca	19 L 488223 8361443	164	379	16	59	37	136
B	Pelechuco	19 L 492374 8361658	455	981	121	256	261	552
C	Quelwa Cota	19 L 502724 8340982	13	36	0	25	0	69
D	Cooca	19 L 559117 8254460	116	471	56	95	227	386
E	Uma Palca	19 K 582696 8224231	130	262	3	25	6	50
F	Campamento la Union	19 K 581228 8203359	8	39	2	8	10	39
G	Santa Roza	19 K 678920 8124950	232	241	1	7	1	7
G	Molinos-Pongo	19 K 683606 8120922	386	672	74	271	129	472
G	Quime	19 K 689983 8121558	1373	3131	55	265	125	604
H	Rodeo	19 K 674456 8114364	65	189	2	56	6	163
H	Bella Vista	19 K 674368 8108942	103	264	73	98	187	251
Total			3126	6909	438	1209	1095	2863

3.3.5 Preliminary risk assessment of potential future lakes in the Bolivian Cordillera Oriental

In the previous sections, the qualitative hazard of the potential future lakes and the impacts for downstream communities have been estimated. In Table 3.5, all qualitative evaluations for future lake hazard and community impacts are presented. Next, in Fig. 3.17 the final risk assessment results are presented for the two different impact scenarios (optimistic and pessimistic).

The riskiest potential future lake in the Bolivian Cordillera Oriental according to the scheme implemented here is A (located in the northernmost part of the Cordillera Apolobamba), which obtains medium risk even in the optimistic scenario, and is rated as medium risk in the pessimistic scenario Table 3.5. Potential future lakes C, F and G appear as low risk in the optimistic scenario but are graded as medium risk in the pessimistic scenario. Finally, potential future lakes B, D, E, H are rated as low risk for both optimistic and pessimistic scenarios Table 3.5.

Table 3.5. Qualitative evaluation of lake hazard and community impact parameters for both scenarios (optimistic scenario and pessimistic scenario) in the event of hypothetical future floods.

Basic characteristics			Hazard (1-3)				Impact (1-3)	
Potential lake	Cordillera	Potential lake coordinates (UTM)	Volume	Steepest slope surrounding lake	Distance between lake and steepest slope	Total hazard (3 - 9)	optimistic scenario (1-3)	pessimistic scenario (1-3)
A	Apolobamba	19 L 478977 8379255	2	3	2	7	2	2
B	Apolobamba	19 L 482645 8361023	1	1	1	3	2	2
C	Apolobamba	19 L 498566 8339169	2	1	2	5	1	2
D	Real	19 L 552119 8249797	1	1	1	3	2	2
E	Real	19 K 576357 8220741	1	1	1	3	1	2
F	Real	19 K 588734 8200961	2	3	1	6	1	2
G	Tres Cruces	19 K 676071 8124915	1	1	1	3	2	3
H	Tres Cruces	19 K 674640 8121348	2	1	1	4	2	2

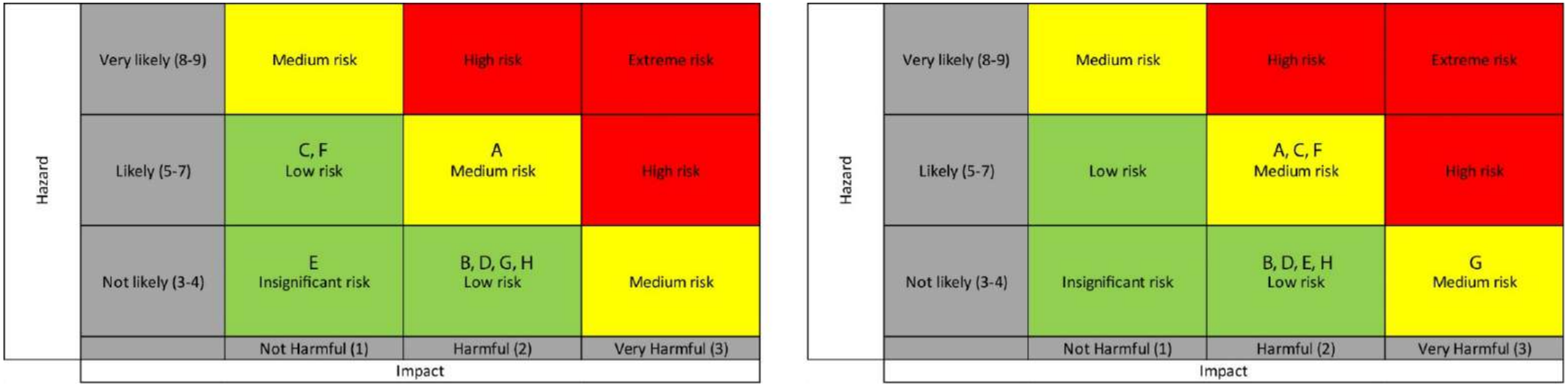


Fig. 3.17. Matrix illustrating the level of risk from each potential future lake. Left: optimistic scenario, Right: pessimistic scenario.

3.4 Discussion

3.4.1 Glacier shrinkage and impacts on water resources in the Bolivian Cordillera Oriental

This work provides an estimate of recent glacier change across the entire Bolivian Cordillera Oriental. Glacier area of the Bolivian Cordillera Oriental has continued to recede from 2014 to 2018. Specifically, Cook et al. (2016) found that the glaciated area had shrunk by around 5.0 % from 2010 to 2014; here, it has been shown that the rate of recession has since increased to around 6.7 % between 2014 and 2018. The total glacier area shrinkage from 1986 to 2018 for the three cordilleras (Apolobamba, Real, Tres Cruces) is ~47 % (i.e. 1.46 % a^{-1}).

From 1986 to 2018, the smaller east-facing glaciers shrank faster than the larger west-facing glaciers of the Bolivian Cordillera Oriental. Specifically, the area of east-facing glaciers has decreased from 258 km^2 to 128 km^2 (i.e. 50 %), and from 271 km^2 to 153 km^2 (i.e. 44 %) on the west-facing side. The precise reasons for differences in mass balance across the range divide are unclear, but some possible explanations are advanced here. In the Bolivian Cordillera Oriental, a rain shadow phenomenon occurs between the east- and west-facing sides (Houston and Hartley, 2003). The easterly wind, coming from the Amazon basin, pushes air over the mountains, and becomes colder with increasing altitude; therefore, moisture condenses and generates precipitation on the eastern slopes. When crossing the range divide, the air becomes warmer and drier as it descends on the west-facing slopes; these slopes receive less precipitation (Garreaud et al., 2009). Nevertheless, due to recent warming conditions in the region, an increasing proportion of precipitation may be falling as liquid (rain) rather than solid (snow), which could intensify ablation and lead to increasing glacier mass loss (Favier et al., 2004). Further, in the Peruvian Cordillera Blanca, Kaser et al. (2005) underline that east-facing slopes are exposed to the morning sun and therefore receive higher rates of solar radiation than west-facing slopes; important turbulent flows and convective clouds develop in the west, leading to shading during the afternoon and a local decrease in incident solar radiation.

Altitudinal controls on mass balance have also been investigated here. Veettil et al. (2018) estimated glacier area changes for different altitude classes for the Bolivian Cordillera Oriental from 1975 to 2016, and their findings are similar to those from this study. Notably, they find that >90 % of the ice-covered areas below 5000 m asl. in the Bolivian Cordillera Oriental were lost, whereas it has been found in this study that 83 % of glacier cover at these altitudes has been lost from 1986 to 2018. Hence, only 7 km^2 of glacier ice remains below 5000 m asl. in the Bolivian Cordillera Oriental. Veettil et al. (2018) also found an 18 % glacier area loss from 1975 to 2016 in the >5500 m asl. altitude class. In this study, slightly higher shrinkage (23 %) is observed in the same altitude class from 1986 to 2018. Glaciers situated below 5400 m asl. represent the majority of ice cover in the tropical Andes covering half of the glacierized area and are likely to disappear in the coming decades (Soruco et al., 2009; Rabatel et al., 2013; Vuille et al., 2018).

In the neighbouring Vilcanota-Urubamba basin of the Peruvian Andes, Drenkhan et al. (2018) applied a low-emission (RCP2.6) and a high-emission (RCP8.5) IPCC scenario to observe potential glacier extent. They found that future glacier areas could decrease substantially by a further ~41 % (RCP2.6) to ~45 % (RCP8.5) until 2050, and by ~41 % (RCP2.6) to ~93 % (RCP8.5) by 2100. Therefore, climate scenarios on glacier shrinkage tend to illustrate moderate impacts for the mid-21st century, and very significant impacts towards the end of the century in the Peruvian Andes.

In another study, Yarleque et al. (2018) analysed the future state of Quelccaya Ice Cap (QIC), which is representative of many low-elevation glacierized sites in the tropical Andes (~5300–5680 m asl.). Using the same high-emission (RCP8.5) scenario as Drenkhan et al. (2018), they underline that from the mid-2050s onwards, the ELA will be located above the QIC summit and increasingly negative mass balances will persist for most tropical glaciers of similar elevations like the Bolivian Cordillera Oriental. Vuille et al. (2018) predict a similar ELA rise (at around 5700 m asl.) towards the end of the 21st century, for the high-emission scenario RCP8.5 for the Zongo glacier in the Cordillera Real.

These alarming results thus confirm the rapid area changes of Bolivian glaciers, with important implications for the sustainability of water supply and ecosystem services in the region. The need for appropriate modelling and planning across all Andean communities who receive a proportion of their water resources from glaciers (especially in the dry season) is illustrated here since recent studies show that projected future glacier shrinkage will lead to a long-term reduction in dry season river discharge from glacierized catchments (Rangecroft et al., 2013; Soruco et al., 2015; Buytaert et al., 2017; Vuille et al., 2018). Cities like la Paz and El Alto are in the most vulnerable position since population in Bolivia is projected to rise from ~11.5 million to ~16 million by 2050 with the biggest rise observed in urban centres (United Nations World Population Prospects, 2017) following also the rural-to-urban migration trend (Kaenzig, 2015). Moreover, McDowell and Hess (2012) underline that many factors play a role in water shortages like the farmers crop choices (with different crops requiring different quantities of irrigation water), glacier runoff reduction, as well as the difficulty of distinguishing between irrigation from precipitation or the use of glacier runoff. Glacier shrinkage in the Bolivian Cordillera Oriental may have impacts for the economy as well. For example, hydropower generation in La Paz and El Alto depends to some extent on glaciers (Liniger et al. 1998; Painter, 2007). In addition, the disappearance of glaciers attracting tourism, such as the Chacaltaya in Cordillera Real, which used to be the site of the highest ski lift in the world since 1939 (Chevallier et al. 2011) is also another issue of concern. Similar issues have been noticed in the neighbouring Peruvian Andes (Mark and Seltzer, 2003; Mark et al., 2005; Drenkhan et al., 2015). Another issue could be impact on the biodiversity hotspots of the Andean bofedales (high-altitude peat bogs and wetland ecosystems), which are supplied from glacier meltwater, and which host rare plants and animals as well as offering valuable water resources to indigenous population. (Squeo et al., 2006; Garcia et al., 2007).

Long-term monitoring of glaciers of the Bolivian Cordillera Oriental is essential. On-site measurements such as Ground Penetrating Radar (GPR) studies, which only exist today for the Zongo glacier are required for different Bolivian glaciers in order to offer validation of estimations from shear stress and other ice-thickness modelling approaches (Linsbauer et al., 2012). Veettil et al. (2018) underline the need for these measurements in order to establish accurate projections for critical periods of water scarcity in semi-arid regions. Even though the Servicio Nacional de Meteorologia e Hidrologia (SENAMHI) provides climatic data (e.g. temperature, precipitation) from a large number of meteorological stations around Bolivia, lack of stations located in high-altitudes (>5000 m asl.) makes the climate and glacier change projections a difficult task. A parameter of interest for future studies focusing on glacier change in Bolivia, as previously undertaken by Bolch et al. (2010) and Paul et al. (2011) could be the influence of glacier aspect, due to differences it provokes on solar radiation. Veettil et al. (2018) have observed that shrinkage rate of south-facing glaciers was low compared to north and north-east facing glaciers, which is similar to the range division results from this study, nevertheless aspect factors must be studied in further detail. In addition, glacier hypsometry which according to Rivera et al. (2014) describes the distribution of elevation of land with respect to sea level and controls the mass balance elevation distribution over a glacier could also be used as glacier characteristic parameter. It is determined by valley shape, topographic relief and ice volume distribution. The altitudinal distribution of a glacier controls how sensitive it will be to a rise of the ELA. In detail, glaciers with a large and flat accumulation area will be more sensitive to a small increase in ELA than glaciers with a steeper accumulation area (Jiskoot et al., 2009). Therefore, numerous studies suggest that glacier hypsometry can be used as a first-order estimator of mass-balance rate sensitivity to ELA change for unmeasured glaciers (e.g. Davies et al., 2012; De Angelis, 2014; Carrivick et al., 2016).

3.4.2 Proglacial lake development in the Bolivian Cordillera Oriental

As glaciers retreat, the number of proglacial lakes (located within 500 m from glacier margins) has increased. Here, it has been shown that four new lakes have appeared during the period 2014-2018. In addition, this study has shown (section 3.3.2) that 68 lakes could appear as glaciers recede.

Proglacial lakes in contact with glaciers, cause a faster and larger magnitude change in glaciers (Tsutaki et al., 2011; Carrivick et al., 2013; Truffer and Motyka, 2016; Carrivick et al., 2017). All glaciers terminating in water lose important volume of ice at their terminus, either through calving processes or direct melt from the contact with water (Truffer and Motyka, 2016). These processes are explained in detail by Carrivick et al. (2013). Therefore, the proglacial lakes that will appear according to our estimations in the Bolivian Cordillera Oriental could influence accelerated glacier shrinkage in the future.

Equally, however, these lakes may offer future water storage that could be utilised for water and energy supply needs (Haeberli et al., 2016). Therefore, studies focusing on the short and long-term risk or opportunity of these lakes to local population could be of interest. The potential future lakes located in the Bolivian Cordillera Oriental could contain an estimated 0.055 km^3 of water volume and could be used as water resources for local population in the future.

3.4.3 Future GLOF risk in the Bolivian Cordillera Oriental

For the first time, GLOF risk from 68 potential future lakes that might appear as glaciers retreat has been estimated. Between ~1100 and ~2900 people might be affected by GLOFs according to the optimistic and pessimistic scenarios respectively. In detail, the Cordillera Tres Cruces might suffer the greatest impacts since ~450 people could be affected from the optimistic scenario and ~1500 from the pessimistic one. Next, ~400 people could suffer the effects of GLOFs in the Cordillera Apolobamba from the optimistic scenario whereas ~900 might be affect from the pessimistic scenario. Lastly, in the Cordillera Real the affected people numbers are smaller, with ~250 people affected by the optimistic scenario and ~480 people from the pessimistic one. It is suggested that ongoing monitoring of the eight locations that potential future lakes could appear should take place and the local population should be notified. It is worth mentioning that some communities (Pelechuco, Aguablanca, Puina) are also under threat from existing proximal lakes (see Kougkoulos et al., 2018a; 2018b) and by consequence if the lakes described in this study were to appear then multi-lake assessments should take place to guarantee appropriate mitigation measures for the population living in these communities. It is worth mentioning also that the potentially affected communities in the three Cordilleras present different characteristics, with the communities in the Tres Cruces being situated in lower altitude and containing more services than the communities of the Cordillera Apolobamba with scattered build-up areas and longer distances from large urban centres. Therefore, on the ground vulnerability analysis (e.g. Frey et al., 2016; Wang et al., 2015) would be an interesting research input for the Bolivian Cordillera Oriental GLOF risk assessment.

Even though potential future lakes have never been assessed before in Bolivia, GLOF risk has received more attention in recent years (Cook et al., 2016; Kougkoulos et al., 2018a; 2018b) following a GLOF event in 2009 at Keara when an ice-dammed lake drained catastrophically, affecting the downstream village, (Hoffmann and Weggenmann, 2013). Research by Drenkhan et al. (2019), focusing on the Peruvian Andes, evaluated (for the first time) the risk from glacial lakes before they have emerged from under glaciers but didn't give any estimations on population numbers being impacted from the potential GLOFs which was attempted here. In the context of ongoing glacier shrinkage, it is essential risk assessments focusing on GLOFs from potential future lakes take place in other mountain ranges around the world (e.g.

Himalaya, Alps etc.) using a combination of risk matrices like the ones provided by Worni et al. (2013), Rounce et al. (2016), Drenkhan et al. (2018) and this study (Fig. 3.17) while also developing assessments that will focus on estimating the potential numbers of people impacted like it is done here using MC-LCP.

3.5 Conclusion

This Chapter extends the glacier area and proglacial lake development dataset of Cook et al. (2016), illustrating that the negative mass balance trend of the last ~30 years is continuing, and the number and size of proglacial lakes increasing. The glaciated areas have decreased by a further 6.7 % in the Bolivian Andes from 2014 to 2018, and four new proglacial lakes have appeared, all of which are situated in the Cordillera Apolobamba. The east-facing side of the Cordillera Oriental is experiencing faster glacier shrinkage, with areas decreasing from 258 km^2 to 128 km^2 (50 %) whereas the west-facing side has experienced glacier area shrinkage from 271 km^2 to 153 km^2 (44 %). In terms of the altitudinal controls, glaciers situated under 5000 m asl. in the Bolivian Cordillera Oriental have already become extinct and only small ice patches remain, representing an area of 7 km^2. Glaciers situated from 5000 to 5500 m asl. have shrunk from 376 km^2 to 199 km^2 (47 %). Glaciers situated over 5500 m asl., declined in area from 100 km^2 to 73 km^2 (23 %). Glacier retreat will probably lead to numerous water-related issues for drinking water, agriculture and hydropower, and future studies should focus on evaluating glacier runoff from glacier volume change on a regional and basin scale. This study also provides a risk assessment of potential future glacial lakes. This was achieved using open-source, freely available data and software. Google Earth and the GlabTop method have been used to verify locations of lakes, lake parameters and estimate potentially impacted population numbers. The upscaled version of the SRTM DEM (12.5 m resolution) from Alaska Fairbanks was used in order to be combined with the simple geometric model (MC-LCP) for the first-order future lake risk assessment. 68 potential future lakes have been identified from which eight lakes have population downstream. Modelling of impacts on the 12 downstream communities, with two sensitivity scenarios, one representing low intensity (optimistic scenario) and one representing high intensity (pessimistic scenario) has shown that between ~1100 and ~2900 people could be affected by flooding if all potential future lakes were to burst. After the evaluation of the hazard parameters for the eight future lakes and the impacts on downstream communities, the risk assessment demonstrated that future lake A (upstream from the community of Puina) could pose the highest risk (medium) for both scenarios, and therefore its potential formation should be studied in more detail. In addition, lakes C, F and G turn from low risk (optimistic scenario) to medium risk (pessimistic scenario) and if they actually appear it is vital that future monitoring take place. Potential lakes B, D, E, H do not seem to present significant risk under current conditions but it is suggested that they are re-evaluated in the future. After examining GLOF risk from lakes that could potentially appear in the future, the next two Chapters (4 and 5) are dedicated on the modelling of the risk from current, already existing lakes identified in Cook et al. (2016) and in this Chapter.

Chapter 4

Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes

(Chapter published - see Appendix 1.1)

4.1 Introduction

In the previous Chapters (2 and 3), it was demonstrated that glaciers in most parts of the world are receding and thinning in response to climate change and that the Bolivian Cordillera Oriental is not an exception. Consequently, there has been a general trend of increasing glacial lake number and size in many regions in recent times. Glacial lake outburst floods (GLOFs) may occur where the impounding dam (ice, rock, moraine, or combination thereof) is breached or overtopped. Thousands of people have lost their lives to such events in the last few decades, mostly during the 1941 GLOF at Huaraz, Peru, and the 2013 Kedernath event, India (Richardson and Reynolds, 2000; Allen et al., 2015; Carrivick and Tweed, 2016). Given the risk posed to downstream communities, industry and infrastructure in deglaciating mountain ranges worldwide, there has been an intensification of research interest in GLOFs (Emmer and Vilímek, 2013), with many such studies seeking to estimate GLOF hazard or risk for individual lakes or in specific regions including North America (Clague and Evans 2000; O'Connor et al., 2001; McKillop and Clague, 2007a,b), South America (Emmer and Vilímek, 2013; Anacona et al., 2015; Cook et al., 2016; Emmer et al., 2016a; Frey et al., 2016), the European Alps (Huggel et al., 2004; Frey et al., 2010), central Asia (Bolch et al., 2008; Mergili and Schneider, 2011; Petrov et al., 2017), and the Himalayas (Wang et al., 2008; Ives et al., 2010; ICIMOD, 2011; Ashraf et al., 2012; Worni et al., 2013; Watson et al., 2015; Aggarwal et al., 2016; Rounce et al., 2016).

Existing GLOF hazard and risk assessments are usually designed for specific purposes (e.g. estimating hazard, susceptibility or risk), specific regions or sites, specific lake contexts (e.g. ice-dammed or moraine-dammed), or require certain types, amounts, or detail of input data, or some combination of the above. These tailored risk assessments are very valuable for their stated purpose, but because of their specific conditions, the extent to which these techniques can be applied to other areas or lake types is uncertain, which itself often necessitates the development of additional region-, site-, or context-specific risk or hazard assessments. In addition, there is often a lack of transparency about why specific criteria are chosen, indicating that hazard and risk assessments are sometimes subjective in their design (McKillop and Clague, 2007a, b).

Nonetheless, some hazard and risk assessments, although developed initially for, and applied to, specific regions, have been designed in such a way that they can be applied elsewhere. Most are designed for moraine-dammed lakes. Notable examples include those of McKillop and Clague (2007b), Mergili and Schneider (2011), and Rounce et al. (2016). McKillop and Clague (2007b) developed an objective method for assessing outburst flood hazard from moraine-dammed lakes in British Columbia, which uses remote sensing methods. Nevertheless, as a hazard assessment it does not evaluate impacts, exposure, vulnerability or risk, and cannot be applied to bedrock- or ice-dammed lakes, which may also exist within the same region. Mergili and Schneider (2011) developed a GLOF hazard assessment based on remote sensing data that could be applied to any lake type, but their method does not consider impacts on humans or infrastructure. Rounce et al. (2016) presented an objective and repeatable method for GLOF hazard and impact assessment, but this was based on moraine-dammed lakes only.

The purpose of this study is to present a decision-aid procedure that can be employed to identify those lakes within any given region that represent the greatest GLOF threat to downstream communities and infrastructure. This procedure, which employs Multi-Criteria Decision Analysis (MCDA), is not specific to any one glacial lake type, which is desirable because it permits the relative threat of impact to be assessed simultaneously for moraine-, ice-, and bedrock-dammed lakes, all of which may exist within the region of interest, as well as composite forms. This enables the generation of standardised results and the determination of appropriate action across the spectrum of glacial lake types. As with some existing GLOF hazard and risk assessments, our MCDA method also uses freely and widely available data and software, without the need for detailed site knowledge, nor field-derived data. As explained in Section 2, MCDA involves the application of strict rules about the use of exhaustive, non-redundant and consistent criteria through the formulation of a 'Description Problem', meaning that subjective selection of criteria is minimised. Another key advantage of the software used for MCDA is that sensitivity analyses are readily undertaken such that the robustness of the model and its assumptions can be evaluated. To our knowledge, sensitivity analysis has not been undertaken for any previous GLOF hazard or risk assessment. It is envisaged that our method is most appropriately applied to regions where a variety of glacial lake types exist so that their relative threat can be assessed simultaneously, where field data are sparse or non-existent, and as a preliminary assessment of the threat posed by GLOFs to people or infrastructure. Once the most dangerous lakes are identified, future detailed field campaigns, flood modelling, and risk mitigation strategies can be employed. An example of where such an approach would be of value is the Bolivian Andes (Cook et al., 2016) where GLOFs from a range of glacier lake types pose a possible threat to downstream areas, but field data are sparse, and collection of such data would be complicated by poor accessibility to sites.

Our objectives are: (1) to define a set of robust (i.e. exhaustive, non-redundant, consistent) susceptibility and potential downstream impact criteria that will be used to define GLOF risk; (2) to use these criteria to assess GLOF risk for 22 lakes around the world and compare our results with those of previous GLOF risk and hazard studies; (3) to undertake sensitivity testing of the MCDA model in order to evaluate the robustness of the method; and (4) apply our model to assess the risk posed by 25 lakes in the Bolivian Andes, which represents a case study of how our model could be used.

A range of terms have been used interchangeably and inconsistently in GLOF 'hazard' and 'risk' studies. These include 'hazard', 'risk', 'susceptibility', 'danger', 'threat', 'impact', 'exposure', and 'vulnerability'. Further, definitions of 'hazard' and 'risk' can vary significantly between different branches of risk management science. In the natural sciences, for example, 'risk' is often taken to be the product of hazard and vulnerability, and sometimes exposure also (e.g. IPCC, 2014); however, international guidelines for the broad and varied fields of risk management science do not necessarily subscribe to such algorithms (see ISO 31000:2009 and The Society for Risk Analysis glossary). For the purposes of our MCDA model, the physical properties of the glacial lakes are considered, and the characteristics of the surrounding landscape and environmental context that may promote or trigger a GLOF event, to be the 'susceptibility' factors that drive the 'hazard' (i.e. a GLOF). The criteria associated with effects on downstream communities in our MCDA model are termed 'potential downstream impacts'. Whilst the product of susceptibility and downstream impacts do not equal risk according to the aforementioned algorithm sometimes used in natural risk science, the term 'risk' is used here to refer to consideration for, and combination of, impacts and susceptibility. This is a convenient short-hand term, and remains consistent with the more general definitions of risk laid out in ISO 31000:2009.

4.2 Methodology

4.2.1 Background to setting an MCDA problem

MCDA is a sub-field of operations research and management science that focuses on the development of decision support tools and methodologies to resolve complex decision problems. It has been applied previously across a number of environmental and natural disaster related problems including floods, landslides, avalanches and water management (e.g. Merad et al., 2004; Marinoni, 2005; Lin, 2008; Akgun 2010; Behzadian et al., 2010; Huang et al., 2011; Stecchi et al., 2012; Tacnet et al., 2014; Brito and Evers, 2016). It is notable that MCDA has not yet been applied to assess GLOF risk. Specifically, MCDA can be applied across a region that contains numerous glacial lake types in order to determine which lakes, if any, should be selected for more detailed analysis, monitoring, or remediation work. The use of freely available tools and datasets, and the ease and relatively rapid deployment of our MCDA approach makes this an effective and efficient technique in areas where detailed knowledge and field data are limited.

In MCDA, a typical problem would be the task of defining the risk between a finite set of decision alternatives (e.g. determining, from a population of glacial lakes, which lakes could generate dangerous GLOFs), each of which is characterised by a set of criteria that must be considered simultaneously (Ishizaka et al., 2012). In this case, all alternatives are considered (i.e. glacial lakes) in a region that are characterised by a set of criteria (e.g. regional seismic activity, dam stability, potential loss of life, etc.). In practice, problems faced by experts or decision-makers in natural hazard or risk management can be a combination of four basic problems (Roy, 1996):

a) **Description Problem:** This is used in order to provide a number of alternatives (e.g. dangerous glacial lakes) and a suitable set of criteria, without making any recommendation about the final decision (e.g. which lakes represent the highest risk). Criteria that will be used in the MCDA are chosen according to past literature and a set of guidelines that will be discussed in section 2.2.
b) **Sorting Problem:** Alternatives (i.e. glacial lakes) are sorted into ordered, pre-defined categories. A sorting problem can also be used for screening in order to

reduce the number of alternatives that are to be considered. For example, all lakes within the study area are sorted according to GLOF risk for downstream communities with categories such as “high risk”, “medium risk”, and “low risk”.

c) **Ranking Problem:** Alternatives (i.e. glacial lakes) are classified from highest to lowest risk; equal ranks are possible. For example, all lakes in the study area are ascribed a numerical value from 1 to *n* depending on their level of GLOF risk to downstream communities, but some lakes may have risk equal to one another and so share the same rank value.

d) **Choice Problem:** This is used to select a single alternative or to reduce the group of alternatives to a subset of equivalent or incomparable alternatives. An example would be to select a single lake with the highest risk to downstream population; all other lakes would be excluded from further analysis.

Previous studies of GLOF hazard or risk have used a wide range of criteria, which reflects variability in the type and amount of data available, and the specific objectives of the assessment procedure (e.g. evaluating hazard or risk, across a region or individual site, and for different lake contexts). Hence, the first task of this study can be framed as a Description Problem, where the main (sub-) criteria that determine the risk of a lake outburst to downstream communities must be defined, with consideration for the range of assessment criteria used in previous studies.

Next, these criteria will be used to frame a Sorting Problem whereby lakes will be classed according to high, medium or low risk, which can be used to narrow future research or mitigation focus onto the most dangerous lakes. The Sorting Problem has been chosen in this study instead of ranking or choice problems because it offers the possibility of evaluating a large set of lakes, but also a single lake. The Ranking Problem suffers from the shortcoming that at least two lakes need to be studied in order for the assessment to take place; the Choice Problem will only define the highest risk lake. Our MCDA approach for GLOF risk is designed to be intuitive, to use freely available datasets, and be applicable to any glacial lake irrespective of dam type or region of the world.

4.2.2 The description problem: determining the criteria that define GLOF risk

Previous reviews of GLOF hazard and risk assessments have highlighted how a wide variety of criteria have been used in different studies to determine GLOF risk (e.g.

Emmer and Vilímek, 2013; Rounce et al., 2016). Others have gone further, suggesting that many assessments are made through subjective and non-transparent selection of criteria (McKillop and Clague, 2007b). MCDA alleviates this issue to some extent by developing a "coherent set" of criteria. In order to achieve this, the following properties need to be fulfilled (Roy, 1996):

- **Exhaustiveness:** all possible criteria are taken into account, and nothing important is left out. For example, a criterion, such as rockfall/landslide susceptibility, is actually a composite of multiple criteria (e.g. slope steepness, seismic activity, etc.) (Fig. 4.1). Hence, such composite criteria should be split into separate criteria to avoid bias in the final estimation of risk. This has not always been done in previous studies (e.g. Costa and Schuster, 1988; Huggel et al., 2004; Bolch et al., 2008; Emmer and Vilimek, 2013; Aggarwal et al., 2016; Rounce et al., 2016). shows the exhaustive list of 79 criteria from which 13 have been selected.
- **Non-redundancy:** no double counting; all the unnecessary criteria must be removed. Some assessments effectively examine the same criteria twice, which biases the risk assessment. For example, glacier snout steepness and presence of a crevassed glacier snout above the lake both lead to a greater probability of ice calving into the lake, which raises the risk of a GLOF (e.g. Grabs and Hanisch, 1993; Zapata, 2000; Wang et al., 2011). However, these two criteria are strongly related - steeper glaciers will generally flow faster, which causes more crevassing, and greater ice calving potential. Therefore, only one representative criterion should be evaluated.
- **Consistency:** the criteria must not hide any preferences. A criterion can only have a positive or negative effect on the choice of alternative (e.g. lake), but can never have both effects simultaneously. For example, glacier shrinkage can have a two-way effect. For moraine-dammed lakes, glacier shrinkage will reduce the risk of calving or ice/snow avalanches into the lake, and hence reduce the risk of a GLOF produced by a displacement wave. But, for ice-dammed lakes, glacier shrinkage can increase the risk of GLOFs because the ice dam disintegrates or becomes more susceptible to flotation or tunnelling by meltwater (e.g. Tweed and Russell, 1999). Hence, criteria need to be selected such that their effects operate in the same direction. This rule has not been

used yet in previous assessments since these studies do not usually perform an evaluation across multiple dam types. Nevertheless, this is important in our study as the MCDA method used here is applicable across all dam types.

In an attempt to meet these characteristics, a list of all the criteria that have previously been used in GLOF risk and hazard assessments was compiled (Table 4.1). Several studies (e.g. Huggel et al., 2004; Bolch et al., 2008; Mergili and Schneider, 2011; Emmer and Vilímek, 2013; Worni et al., 2013; Rounce et al., 2016) have also compiled and/or reviewed a number of these criteria. However, in many studies, the final selection of criteria that are used to make the risk assessment is often made (1) seemingly on a subjective or non-transparent basis, or (2) based on the frequency of use in previous studies (e.g. a tally chart). To some extent, this reflects specific local or regional needs or issues, or specific data requirements or availability. But for areas where there are limited data or knowledge, the MCDA guidelines outlined above serve to reduce user bias in the selection of criteria by first considering all available criteria, and streamlining them to avoid issues of non-exhaustiveness, redundancy, and non-consistency. Table 4.1 was generated from 30 studies and lists 79 factors in total. Through consideration of their exhaustiveness, non-redundancy, and consistency, 13 criteria that can be used for GLOF risk analysis of any lake were identified, in any part of the world, from freely available data or satellite imagery. Hence, several criteria were rejected because they were either non-exhaustive, redundant, or non-consistent, would have necessitated fieldwork, or that were specific to a region or a particular lake type. Fig. 4.1 illustrates how, from the 13 criteria, lakes are assessed according to their GLOF risk. Details about each criterion are provided in the Supplementary Data - Appendix 4.1. If local data exist for any of these criteria, their use is strongly encouraged.

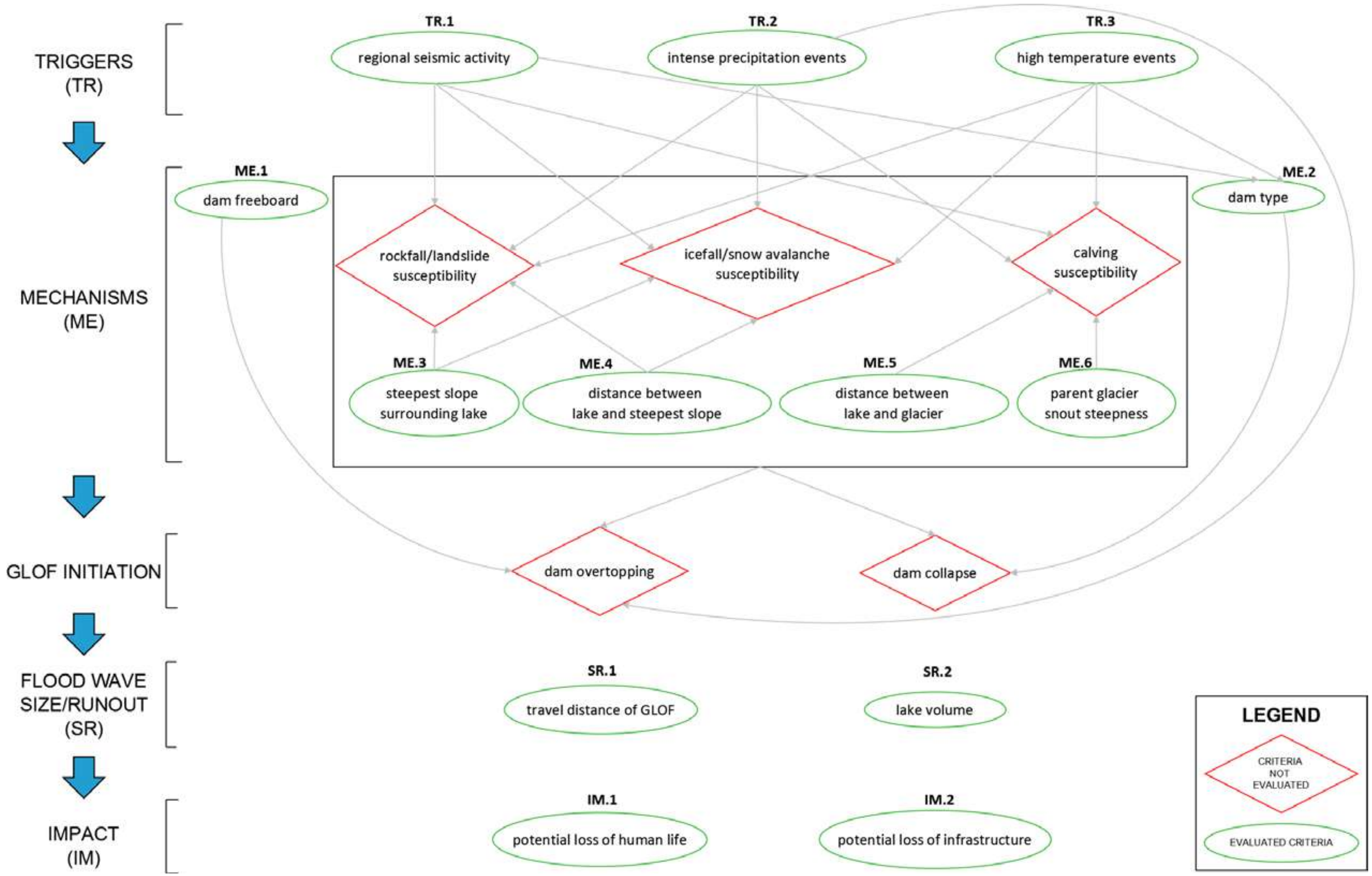


Fig. 4.1. Flow diagram of the GLOF risk assessment procedure. Supplementary information about the final set of criteria can be found in Appendix 4.1.

Table 4.1. Review of criteria assessed in previous studies. Top section outlines the process followed to accept or reject a criterion. Middle section shows the results. Bottom section illustrates the literature used. The accepted criteria in the middle section are illustrated in Fig. 4.1.

accepted/rejected criterion	reason	indication
rejected criterion	dam, region or scenario specific	A
	field assessment required	B
	non-exhaustive	C
	redundant	D (with which criterion)
	non-consistent	E
accepted criterion	no issue	✓

ID	criterion	source	accepted/rejected criterion
TR.1	regional seismic activity	4,15,18,28	✓
TR.2	precipitation seasonality (intense precipitation events)	8,13	✓
TR.3	temperature seasonality (high temperature events)	8,13	✓
ME. 1	dam freeboard	2,3,4,5,15,17,18,21,30	✓
ME. 2	dam type	4,8,12,15,17,29,30	✓
ME. 3	steepest slope surrounding lake	6,11,14	✓
ME. 4	distance between lake and steepest slope	9,26	✓
ME. 5	distance between lake and glacier	2,4,5,14,16,24,26	✓
ME. 6	parent glacier snout steepness	2,4,11,13,16	✓
SR.1	travel distance of GLOF	8,17,23,28	✓
SR.2	lake volume	4,7,21,26	✓
IM.1	potential loss of human life	28	✓
IM.2	potential loss of infrastructure	28	✓
1	hydrometeorological situation	18	C
2	mass movement into lake/potential for lake impact	1,8,11,18,21,24,30	C
3	snow avalanche/icefall susceptibility	4,7,14,15,17,21,28	C
4	rockfall/landslide susceptibility	2,3,4,14,15,17,21,28	C
5	slope of lateral moraines and possibility of its fall into the lake	2,19	C
6	interconnected lakes/unstable lake upstream	6,18,24,28,30	C
7	calving susceptibility	15	C
8	slope between lake and glacier snout	16	D (with ME.6)
9	crevassed glacier snout above lake	2,3,4	D (with ME.6)
10	stagnant ice at the glacier terminus	14	B
11	area of the mother glacier	13,16	E
12	glacier advance	2	E
13	glacier shrinkage	14	E
14	reaction of the glacier to climate change	11	E
15	contact with glacier	6,26	D (with ME.5)
16	maximum area of inundation	10	D (with SR.1)
17	amount of loose material/maximum debris flow volume	6	B
18	lake area and/or size	4,10,14,19,24,26	D (with SR.2)
19	breach volume	6	B

20	lake area change	11,14,15,28	D (with SR.2)
21	lake depth	4,21,26	D (with SR.2)
22	distant flank steepness of the dam	1,4,13,15,16	A,B
23	width and/or height ratio of dam	3,4,8,10,12,13	B
24	top width of dam	13,19	A, B
25	steepness of moraine	2	A
26	piping/seepage through moraine	2,3,4,7,12,15,19	A,B
27	buried ice in moraine	1,2,7,8,10,11,13	A,B
28	main rock type of moraine	10	A,B
29	moraine slope stabilised by vegetation	1	A
30	supra/englacial drainage	7,30	A,B
31	piping gradient	19	A,B
32	lake perimeter	19	A
33	lake width	19	A
34	dam height	19	A
35	maximum slope of distal face of the dam	19	A,B
36	mean slope between lake and glacier	19	D (with ME.6)
37	mean slope of lake surrounding	19	D (with ME.3)
38	hydrostatic pressure	28	B
39	lake elevation	20	D (with TR.2)
40	nonglacial watershed component	20	D (with TR.2)
41	mean stream size	20	D (with TR.2)
42	drainage density	20	D (with TR.2)
43	mean slope	20	D (with TR.2)
44	population density	22	B
45	livestock density	22	B
46	cultivated area	22	B
47	density of road network	22	B
48	density of agricultural economy	22	B
49	proportion of rural population	22	B
50	percentage of small livestock	22	B
51	road level	22	B
52	building level	22	B
53	regional GDP	22	B
54	financial revenue share of GDP	22	B
55	density of fixed assets investment	22	B
56	female population	25	B
57	population < 6 years of age	25	B
58	population > 60 years of age	25	B
59	literacy rate	25	B
60	unemployment	25	B
61	employment in farming	25	B
62	disabled population	25	B
63	home renters	25	B
64	derelict houses	25	B
65	water availability	25	B

66	medical facilities	25	B
67	education facilities	25	B
68	banking services	25	B
69	access to radio	25	B
70	access to TV	25	B
71	access to internet	25	B
72	access to mobile	25	B
73	access to vehicle	25	B
74	economical vulnerability	27	B
75	social vulnerability	27	B
76	institutional vulnerability	27	B
77	building materials	27	B
78	geology and type of soil	27	B
79	land use laws	27	B

1: Costa and Schuster (1988); 2: Grabs and Hanisch (1993); 3: Clague and Evans (2000); 4: Zapata (2000); 5: O'Connor et al. (2001); 6: Huggel et al. (2002); 7: Reynolds (2003); 8: Huggel et al. (2004); 9: Rickenmann (1999, 2005); 10: McKillop and Clague (2007a, b); 11: Bolch et al. (2008); 12: Hegglin and Huggel (2008); 13: Wang et al. (2008); 14: Bolch et al. (2011); 15: Mergili and Schneider (2011); 16: Wang et al. (2011); 17: Worni et al. (2013); 18: Emmer and Vilímek (2013); 19: Emmer and Vilímek (2014); 20: Allen et al. (2015); 21: Vilímek et al. (2015); 22: Wang et al. (2015); 23: Watson et al. (2015); 24: Allen et al. (2016); 25: Aggarwal et al. (2016); 26: Cook et al. (2016); 27: Frey et al. (2016); 28: Rounce et al. (2016); 29: Carrivick and Tweed (2016); 30: Petrov et al. (2017).

4.2.3 The sorting problem: Past GLOF events and potentially dangerous lakes

Following the identification of appropriate selection criteria from the Description Problem stage, all lakes within a region can be judged according to those criteria in order to determine which lakes, if any, represent a GLOF risk to downstream communities. This can be achieved remotely (i.e. without the need for fieldwork), and without cost, as it is demonstrated below. Our approach can be applied to a single lake or to a complete lake inventory within a region. It would be particularly useful in identifying sites for further detailed field studies, outburst flood modelling, or monitoring. In this study, our method is applied on a number of lakes that had been identified in previous studies as representing a threat to downstream communities. Fig. 4.2 illustrates the steps that need to be followed for the method to be applied in a chosen region. For the trigger criteria (TR.1, 2, 3), the user will need to open the indicated databases (Global seismic hazard map, BIOCLIM variables 4 and 5) in a GIS in order to evaluate the lakes. For all other criteria, Google Earth Pro is sufficient for evaluation. Additional information about criteria evaluation can be found in Table 4.2 and Appendix 4.1.

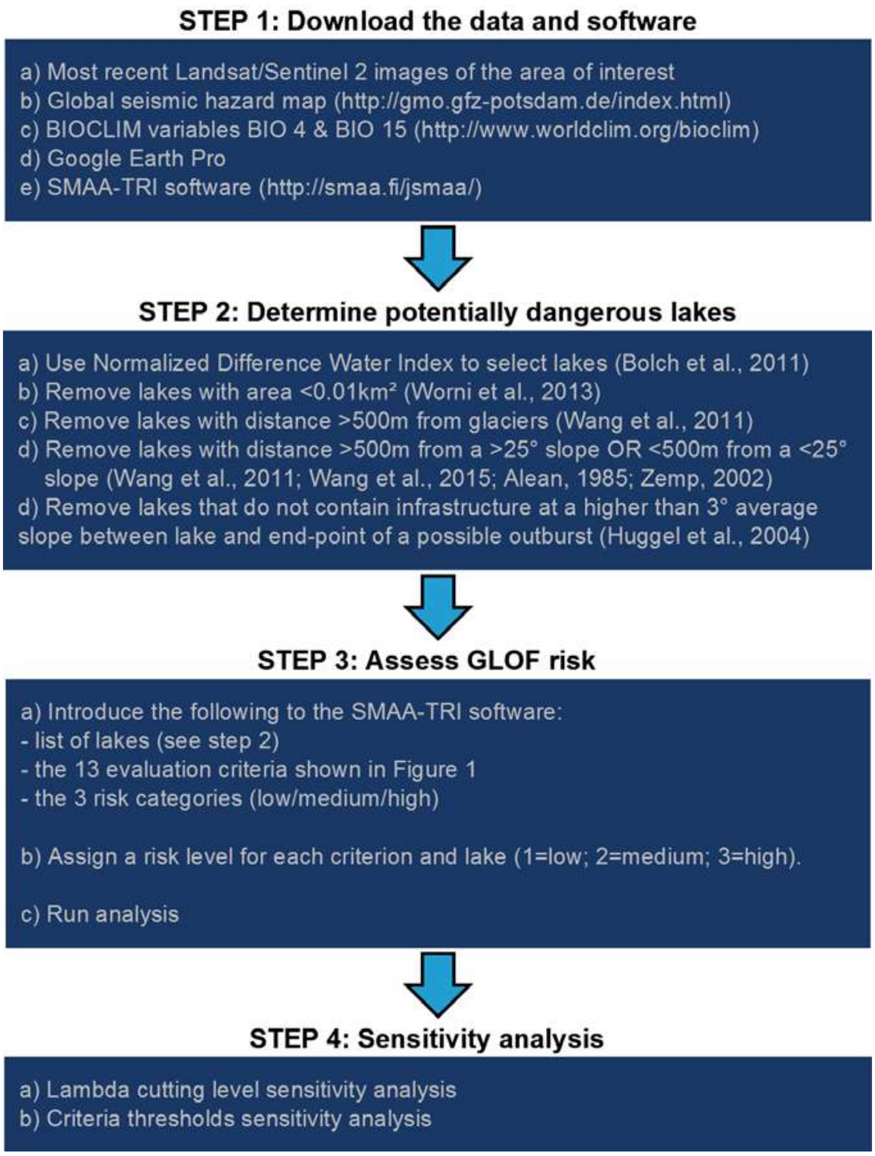


Fig. 4.2. Five-step flow diagram for the Multi-Criteria Decision Analysis (MCDA) method. Step 1: the user downloads all data and software needed for the evaluation; Step 2: the proglacial lake dataset to be analysed is extracted; Step 3: introducing the parameters to the software and computation of the result; Step 4: Sensitivity Analysis

4.2.4 Choice of lakes for testing

Our MCDA method was applied to 22 glacial lakes from a number of locations around the world in order to test and evaluate the performance of the model globally. A mix of lakes that have been the subject of previous GLOF hazard or risk studies was used (where MCDA has not been used), as well as lakes that are known to have generated GLOFs. The 6 GLOF-generating lakes were selected based on two important characteristics:

- There is existing literature describing the downstream impact of the GLOF;

- There is free, high-resolution satellite imagery (e.g. integrated into Google Earth) before the GLOF event, which makes the pre-GLOF lake risk assessment possible.

Of these lakes, one is located in Norway (Flatbreen lake - Breien et al., 2008), one in Bolivia (Keara - Hoffmann and Wegenmann, 2013), one in Peru (Lake 513 - Carey et al., 2012; Klimeš et al., 2014; Vilímek et al., 2015), one in Nepal (Halji lake - Kropácek et al., 2015;), one in Pakistan (Passu lake - Ashraf et al., 2012), and one in India (Chorabari lake - Das et al., 2015). Hence, a wide range of locations are represented.

The remaining 16 lakes have not yet burst but are considered potentially dangerous by other GLOF hazard/risk assessments that have made use of multiple criteria: one is located in Peru (Hanpi k'ocha - Frey et al., 2016), five are located in India (Gopang Gath, Spong Tongpo, Schako Tsho - Worni et al., 2013; Chollamo, Lake 0071 - Aggarwal et al., 2017), eight in Nepal (Imja Tsho, Tsho Rolpa, Thulagi Tsho, Dig Tsho, Lower Barung Tsho, Ludming Tsho, Chamlang South Tsho, Chamlang North Tsho - Rounce et al., 2016) and two in New Zealand (Maud lake, Godley lake - Allen et al., 2009). Values for each criterion were assigned for the lakes (see also Supplementary Data - Appendix 4.2, Tables 1 and 2) and the analysis was run using the SMAA-TRI software (see section 2.3.2).

4.2.5 SMAA-TRI software

A range of different software packages and methods have been developed for resolving complex sorting problems in MCDA: e.g. FlowSort (Nemery and Lamboray 2008), ELECTRE-Tri (Mousseau et al., 2000), AHPSort (Ishizaka et al., 2012). ELECTRE-TRI has been used by Merad et al. (2004) to identify zones subject to mining-induced risk; Stecchi et al. (2012) used the same software to assess vulnerability due to ground deformation phenomena. In this study, SMAA-TRI was used (**S**tochastic **M**ulti-criteria **A**cceptability **A**nalysis, http://smaa.fi/), a free-to-download upgraded version of ELECTRE-TRI (Tervonen et al., 2012). SMAA methods allow the tackling of problems with imprecise information, similar to the criteria used in GLOF multi-criteria assessments. Imprecise information means that the value is present but not always with the required precision (Tervonen et al., 2012; Malczewski and Rinner, 2015). A review of all the ELECTRE method packages can be found in Figueira et al. (2013).

4.2.6 Setting risk thresholds and codes for evaluating individual criteria

Table 4.2 presents the threshold values that have been used to define the risk classes for each criterion in the sorting method (see also Supplementary Data - Appendix 4.1). The software allows the user to set the evaluation codes. For this model, three codes where set: 1 (low risk), 2 (medium risk) and 3 (high risk). These values are used to assign each criterion to a predefined risk class, from which a total risk score can be calculated for each lake.

The relative importance of each criterion can differ, and there are numerous methods for determining the relative weights of individual criteria (Saaty, 1977; Chen et al., 2001; Figueira and Roy, 2002). In a natural hazard context, weights are typically determined subjectively by the hazard/risk experts or based on statistical methods (such as regression and principal component analysis) (Chen et al., 2001). However, since there is insufficient empirical evidence by which to determine the relative importance of each criterion in GLOF risk or hazard assessments, the decision was made here not to assign any weights. Nonetheless, this could be undertaken in future studies if understanding of GLOF controlling factors were to develop sufficiently.

Table 4.2. Criteria units, evaluation methods, main risk thresholds and sensitivity analysis thresholds. Details on criteria threshold determination can be found in Appendix 4.1.

ID	Criteria	Unit	Low risk	Medium risk	High risk	Evaluation tool	Sensitivity analysis	Threshold variations for sensitivity analysis
Triggers								
TR.1	regional seismic activity	pga in m/s²	<0.5	0.5-3.9	>3.9	USGS/Global Seismic Hazard Map-GSHAP	✓	<0.5, 0.5-1.9, >1.9
TR.2	intense precipitation events	precipitation seasonality in %	<50	50-100	>100	Bioclim 15 - precipitation seasonality	✓	<25, 25-75, >75
TR.3	high temperature events	temperature seasonality in %	<50	50-100	>100	Bioclim 4 - temperature seasonality	✓	<25, 25-75, >75
Mechanisms								
ME.1	dam freeboard	m	>15	15-5	<5	Google Earth/Bing Maps	not enough detail	
ME.2	dam type	type	bedrock	moraine	ice	Google Earth/Bing Maps	qualitative	
ME.3	steepest slope surrounding lake	degrees	<30	30-45	>45	Google Earth/Bing Maps	✓	<20, 20-30, >30
ME.4	distance between lake and steepest slope	m	500-250	250-10	10-contact	Google Earth/Bing Maps	✓	500-250, 250-50, <50
ME.5	distance between lake and glacier	m	500-250	250-10	10-contact	Google Earth/Bing Maps	✓	500-250, 250-50, <50
ME.6	parent glacier snout steepness	degrees	<15	15-25	>25	Google Earth/Bing Maps	not enough detail	
Flood wave size/runout								
SR.1	travel distance of GLOF	degrees	3-7	7-11	>11	Google Earth/Bing Maps	✓	3-6, 6-9, >9
SR.2	lake volume	m3 * 10^6	<1 * 10^6	1 * 10^6 - 10 * 10^6	>10 * 10^6	Google Earth/Bing Maps for area + equation	✓	<0.1*10^6, 0.1 * 10^6 - 1 * 10^6, >1 * 10^6 (1 order of magnitude lower threshold)
Impact								
IM.1	potential loss of human life	individuals	<10	10-1000	>1000	Google Earth/Bing Maps/web info	✓	<10, 10-100, >100
IM.2	potential loss of infrastructure	infrastructure	agricultural fields, roads etc.	houses, bridges etc.	hydropower, mining camp etc.	Google Earth/Bing Maps/web info	qualitative	

4.2.7 Sensitivity analysis

In MCDA, sensitivity analysis serves to determine how much the uncertainty of the results of a model are influenced by the uncertainty of its input criteria (Saltelli et al., 1999). Sensitivity analysis can be performed using different methods. The robustness of the model can be assessed by analysing its sensitivity to the alteration of parameter λ (lambda), the criteria thresholds, and their assigned weights (Roy, 1993). The criteria used in this study do not hold weights, so the two sensitivity analyses to be undertaken are (1) the alteration of the λ-cutting level, and (2) the variation of the criteria thresholds.

4.2.7.1 Lambda cutting level

The λ-cutting level indicates how many of the criteria have to be fulfilled in order to assign an alternative (i.e. a lake) to a specific risk category, and it can be altered within the software. The cutting level must be set to between 0.5 and 1.0 (Damart et al., 2007); a cutting level of 0.5 means that at least 50 % (i.e. 7 criteria) of the 13 criteria would need to be evaluated as 'high risk' in order to assign a lake in the high risk category overall. Several studies have discussed the assignment of an appropriate cutting level, and it is generally accepted that it should be greater than the highest weight (Figueira and Roy, 2002; Merad et al., 2004; Brito et al., 2010; Tervonen et al., 2012; Sánchez-Lozano, 2014). Since no weights were assigned in this study, a series of scenarios are presented in Table 4.4 where the cutting level is set to 0.65, 0.7, 0.75, 0.8, and 0.85. The objective here is to assess whether any lakes change risk category as the cutting level is changed from its least conservative level (0.65) to its most conservative level (0.85). The percentages in each risk class show the level of confidence with which the software assigns each lake to a class. The higher the percentage, the higher the probability of a lake belonging to that specific risk class. If percentages between two risk classes are equal, then the GLOF risk for that lake will be classified automatically in the higher risk class, since risk analysis is generally a conservative exercise (Merad et al., 2004).

4.2.7.2 Criteria thresholds

The second sensitivity analysis examines the extent to which risk classifications will change if the threshold values used for each criterion are altered (both the original thresholds and the revised thresholds used for the sensitivity analysis can be found in Table 4.2). For this analysis, the λ-cutting level was kept at 0.65, and thresholds were changed for 9 of the 13 criteria; thresholds for the 4 remaining criteria (ME.1, 2, 6 and IM.2) could not be altered either because the resolution of the remote sensing data was insufficient to allow any meaningful threshold changes to be made, or because of the qualitative nature of the threshold limits. A conservative approach was used, whereby the thresholds for the highest levels of risk for each criterion were relaxed in order to determine whether any lakes then fell into the high risk category overall.

4.3 Results

4.3.1 Assessing GLOF risk: an application to past and potential future events

Table 4.3 shows the lakes considered in this study alongside the level of risk posed to downstream communities, which was determined using our MCDA approach. The results show that 11 lakes pose a high risk to downstream communities, six lakes are ranked as medium risk, and five as low-risk. Since susceptibility and downstream impacts are both evaluated in the same computational step, the outcome (risk classes) shows the combination of GLOF impact severity and potential outburst susceptibility. A lake can become classified as high risk either due to high outburst susceptibility parameters, such as elevated regional seismic activity and steep slopes surrounding the lake, or because of severe potential impacts, such as a large population downstream, or the presence of high-value infrastructure.

Table 4.3. Potentially dangerous lakes and selected GLOF events derived from previous studies. Risk level derived from the MCDA method. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific risk class. Low risk = Green, Medium risk = Orange, High risk = Red.

Dangerous lakes - literature	Country	Reference	Coordinates in UTM			Risk Level
Maud Lake	New Zealand	Allen et al., 2009	59 G	459482	5185818	0.97
Godley Lake	New Zealand	Allen et al., 2009	59 G	461555	5188206	0.89
Chholamo	India	Aggarwal et al., 2017	45 R	672675	3099360	0.89
Lake 0071	India	Aggarwal et al., 2017	45 R	676212	3084379	0.58
Hanpi k'ocha	Peru	Frey et al., 2016	18 L	743739	8534059	0.62
Gopang Gath	India	Worni et al., 2013	43 S	708269	3601049	0.92
Spong Tongpo	India	Worni et al., 2013	43 S	658545	3769166	0.70
Schako Tsho	India	Worni et al., 2013	45 R	658915	3095511	0.78
Imja Tsho	Nepal	Rounce et al., 2016	45 R	492610	3085944	0.78
Tsho Rolpa	Nepal	Rounce et al., 2016	45 R	448360	3082066	0.97
Thulagi Tsho	Nepal	Rounce et al., 2016	45 R	253755	3153985	1.00
Dig Tsho	Nepal	Rounce et al., 2016	45 R	459210	3083375	0.99
Lower Barung Tsho	Nepal	Rounce et al., 2016	45 R	509355	3074824	0.97
Ludming Tsho	Nepal	Rounce et al., 2016	45 R	461884	3072885	0.92
Chamlang South Tsho	Nepal	Rounce et al., 2016	45 R	495956	3069986	0.91
Chamlang North Tsho	Nepal	Rounce et al., 2016	45 R	495685	3073227	0.91
Selected GLOF events	**Country**	**Reference**	**Coordinates in UTM**			**Risk Level**
Flatbreen lake - 2004	Norway	Breien et al., 2008	32 V	382775	6817696	0.57
Passu lake - 2007	Pakistan	Ashraf et al., 2012	43 S	489281	4034749	0.65
Keara lake - 2009	Bolivia	Hoffmann and Wegenmann, 2013	19 L	481958	8377253	0.52
513 lake - 2010	Peru	Carey et al., 2012; Klimeš et al., 2014; Vilímek et al., 2015	18 L	219809	8980678	0.65
Halji lake - 2011	Nepal	Kropácek et al., 2015	44 R	545635	3348799	0.79
Chorabari lake - 2013	India	Das et al., 2015	44 R	314434	3403219	0.59

4.3.2 Lambda cutting level sensitivity analysis

The results of this first sensitivity analysis are shown in Table 4.4. All lakes that are already classified as high risk when the cutting level is at 0.65 will not change class with an increase in the cutting level. This is because as the cutting level is increased (0.70, 0.75, etc.), a lower proportion of criteria graded as ‘high risk’ (30 %, 25 %, etc.) are needed in order to classify a lake as ‘high risk’ overall. Lakes classified as medium or low-risk when the cutting level is 0.65 may be reclassified into a higher risk class as the cutting level is increased. Taking the example of the five low-risk lakes, the number of low-risk criteria is sufficiently important to maintain the lakes as low risk no matter what cutting level is used. Two of the lakes classed as medium risk with a cutting level of 0.65 (Keara Lake and Hanpi k'ocha) move into high-risk categories when the cutting level is increased by one increment to 0.7, and a further three when the cutting level is increased to 0.75. Gopang Gath is the only lake that maintains its medium-risk score until the penultimate computational step (λ = 0.80), after which it shifts to high risk (λ = 0.85).

Table 4.4. Sensitivity analysis based on alteration of the lambda cutting level. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific risk class. Low risk = Green, Medium risk = Orange, High risk = Red.

Dangerous lakes - literature	λ-cutting level				
	0.65	0.7	0.75	0.8	0.85
Maud Lake	0.97	0.98	0.97	0.93	0.86
Godley Lake	0.89	0.89	0.84	0.72	0.56
Chholamo	0.89	0.89	0.84	0.73	0.56
Lake 0071	0.58	0.72	0.82	0.87	0.84
Hanpi k'ocha	0.62	0.49	0.64	0.79	0.91
Gopang Gath	0.92	0.83	0.70	0.50	0.44
Spong Tongpo	0.70	0.53	0.38	0.56	0.73
Schako Tsho	0.78	0.88	0.94	0.98	1.00
Imja Tsho	0.78	0.88	0.95	0.98	1.00
Tsho Rolpa	0.97	0.99	1.00	1.00	1.00
Thulagi Tsho	1.00	1.00	1.00	1.00	1.00
Dig Tsho	0.99	1.00	1.00	1.00	1.00
Lower Barung Tsho	0.97	0.99	1.00	1.00	1.00
Ludming Tsho	0.92	0.96	0.99	1.00	1.00
Chamlang South Tsho	0.91	0.96	0.99	1.00	1.00
Chamlang North Tsho	0.91	0.96	0.99	1.00	1.00
Selected GLOF events	**λ-cutting level**				
	0.65	**0.7**	**0.75**	**0.8**	**0.85**
Flatbreen Lake - 2004	0.57	0.68	0.73	0.69	0.55
Passu Lake - 2007	0.65	0.49	0.64	0.79	0.90
Keara Lake - 2009	0.52	0.49	0.65	0.80	0.91
513 Lake - 2010	0.65	0.50	0.65	0.80	0.91
Halji Lake - 2011	0.79	0.88	0.95	0.98	1.00
Chorabari Lake - 2013	0.59	0.73	0.85	0.93	0.98

4.3.3 Criteria thresholds sensitivity analysis

The results of this second sensitivity analysis are shown in Table 4.5. Respectively, Rows A and B indicate the number of lakes that change risk class and change risk classification confidence level when each criterion threshold is modified. Several criteria lead to little or no change to the number of lakes that are re-classified when their thresholds are modified, and only minor changes in the percentage of confidence in each risk class. These are intense precipitation events (TR.2), distance between lake and steepest slope (ME.4), and distance between lake and glacier (ME.5). Altering thresholds for high temperature events (TR.3), GLOF travel distance (SR.1), potential loss of human life (IM.1), and steepest slope surrounding the lake (ME.3), lead to a shift of up to three lakes from low to medium and from medium to high risk, and a change of confidence levels for up to four lakes. Threshold alterations for lake volume (SR.2) and regional seismic activity (TR.1) resulted in the greatest shift in lake risk classification, with three and four lakes respectively changing from medium risk to high risk, as well as four and eight lakes changing confidence levels respectively for SR.2 and TR.1.

Columns C and D in Table 4.5 illustrate, respectively, the number of times each lake changes risk class and confidence level within a class when a criterion threshold is changed. In summary, Maud lake, Godley lake and Chholamo all remain as low-risk throughout the process, but Lake 0071 shifts once from low risk to medium risk. Hanpi k'ocha and Keara lake change from medium to high risk twice, Passu lake three times, and lake 513 five times. Hence, Passu lake and lake 513 appear to be particularly sensitive to certain individual criteria thresholds being changed. Confidence levels remain stable in most cases, with some exceptions; Chholamo and Keara lakes undergo a shift in class confidence level once, and Gopang Gath, Schako Tsho, Flatbreen Lake and Chorabari lake twice. Furthermore, the confidence level changes three times for Maud lake and Halji lake, and four times for Godley lake and Spong Tongpo. Overall, the model results remain robust when thresholds are changed, but some lakes are identified through sensitivity analysis as being particularly sensitive, and hence possibly worthy of careful attention in any risk management decisions or actions.

Table 4.5. Sensitivity analysis of individual criteria as compared to results before sensitivity analysis (as in Table 4.3). Decimal percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk = Orange, High risk= Red). The number of lakes that change A) risk class or B) confidence level for each criterion threshold change is also indicated, and the number of times a lake changes C) risk class or D) confidence level for each criterion threshold change.

Dangerous lakes - literature	Results before sensitivity (as in table 4.3)	TR.1	TR.2	TR.3	ME.3	ME.4	ME.5	SR.1	SR.2	IM.1	C	D
Maud Lake	0.97	0.94	0.97	0.91	0.94	0.97	0.97	0.97	0.97	0.97	0	3
Godley Lake	0.89	0.81	0.89	0.77	0.81	0.80	0.89	0.89	0.89	0.89	0	4
Chholamo	0.89	0.81	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0	1
Lake 0071	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.65	0.58	0.58	1	0
Hanpi k'ocha	0.62	0.58	0.62	0.62	0.62	0.62	0.62	0.62	0.58	0.62	2	0
Gopang Gath	0.92	0.81	0.92	0.92	0.92	0.92	0.92	0.95	0.92	0.92	0	2
Spong Tongpo	0.70	0.53	0.70	0.52	0.70	0.62	0.70	0.70	0.52	0.70	0	4
Schako Tsho	0.78	0.91	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.91	0	2
Imja Tsho	0.78	0.92	0.92	0.92	0.78	0.92	0.92	0.92	0.92	0.92	0	0
Tsho Rolpa	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0	0
Thulagi Tsho	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0
Dig Tsho	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0	0
Lower Barung Tsho	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0	0
Ludming Tsho	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0	0
Chamlang South Tsho	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0	0
Chamlang North Tsho	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0	0
Selected GLOF events	**Results before sensitivity (as in table 4.3)**	**TR.1**	**TR.2**	**TR.3**	**ME.3**	**ME.4**	**ME.5**	**SR.1**	**SR.2**	**IM.1**	**C**	**D**
Flatbreen Lake - 2004	0.77	0.77	0.77	0.77	0.54	0.77	0.77	0.77	0.57	0.77	0	2
Passu Lake - 2007	0.65	0.58	0.65	0.58	0.65	0.65	0.65	0.65	0.58	0.65	3	0
Keara Lake - 2009	0.52	0.58	0.52	0.52	0.52	0.52	0.52	0.59	0.61	0.52	2	1
513 Lake - 2010	0.65	0.58	0.65	0.65	0.58	0.65	0.65	0.59	0.58	0.58	5	0
Halji Lake - 2011	0.79	0.79	0.92	0.79	0.79	0.79	0.79	0.79	0.91	0.92	0	3
Chorabari Lake - 2013	0.59	0.79	0.59	0.59	0.79	0.59	0.59	0.59	0.59	0.59	0	2
A		4	0	1	1	0	0	3	3	1		
B		8	1	3	4	1	0	1	4	2		

4.3.4 Application to a data-scarce region: the Bolivian Andes

Here, the MCDA method was applied to glacial lakes of the Bolivian Andes, which is a region where GLOF risk has not yet been studied in detail, and where there are a range of lake types, and very little information about the nature of the lakes or the environment within which they are situated. Cook et al. (2016) performed a rudimentary assessment of the GLOF threat posed by Bolivian glacial lakes; their work amounts to the completion of Steps 1 and 2 in Fig. 4.2. They identified 137 lakes in total; from these lakes, 25 had population downstream and therefore required further investigation. This list includes a mix of moraine-dammed and bedrock-dammed lakes, although an ice-dammed lake at Keara burst in 2009, and is featured in our earlier model results. To assess GLOF risk for these 25 lakes, the λ-cutting level is set at 0.65 and the criteria thresholds are kept at their initial values. Qualitative values for each criterion were assigned for the lakes (see also Supplementary Data - Appendix 4.2, Table 3)

Table 4.6 illustrates the results of the Bolivian GLOF risk assessment. Overall, one lake is identified as high risk (Murarata – Laguna Arkhata), and two lakes are identified as medium risk (Apolobamba – Pelechuco; Real – Laguna Glaciar). The remainder are graded as low risk.

Table 4.6. Risk levels for potentially dangerous lakes in the Bolivian Andes as identified by Cook et al. (2016). Decimal percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk = Orange, High risk= Red).

Lakes	Coordinates in UTM			Risk level
Apolobamba - Puina	19 L	476504	8384832	0.58
Apolobamba - Pelechuco	19 L	481205	8365591	0.84
Apolobamba - Hilo Hilo 1	19 L	492850	8354529	0.79
Apolobamba - Hilo Hilo 2	19 L	487996	8349572	0.91
Apolobamba - Hilo Hilo 3	19 L	487666	8349316	0.78
Apolobamba - Puyo Puyo	19 L	486275	8351196	0.97
Apolobamba - Taypi Cayuma 1	19 L	491182	8343142	0.92
Apolobamba - Taypi Cayuma 2	19 L	492072	8340807	0.94
Apolobamba - Cholina Cholina 1	19 L	497085	8337363	0.78
Apolobamba - Cholina Cholina 2	19 L	498284	8335884	0.94
Real - Laguna Glaciar	19 L	547085	8249728	0.81
Real - Cocoyo 1	19 L	556846	8251418	0.94
Real - Cocoyo 2	19 L	559120	8249880	0.97
Real - Cocoyo 3	19 L	560553	8247486	0.58
Real - Rinconada 1	19 L	552071	8244232	0.58
Real - Rinconada 2	19 L	550069	8242190	0.58
Real - Laguna Wara Warani	19 K	567694	8222503	0.79
Real - Umapalca	19 K	584186	8220965	0.58
Real - Condoriri	19 K	578927	8210860	0.98
Real - Comunidad Pantini	19 K	612872	8182149	0.97
Mururata - Laguna Arkhata	19 K	624521	8172040	0.58
Tres Cruces - North	19 K	670245	8126070	0.91
Tres Cruces - Mining camp west	19 K	674446	8120893	0.57
Tres Cruzes - Mining camp east	19 K	678278	8121207	0.77
Tres Cruces - Laguna Huallatani	19 K	675910	8118767	0.77

4.4 Discussion

4.4.1 Comparisons with existing GLOF hazard and risk assessments

The level of GLOF risk for 16 lakes that had been identified in previous studies as representing a threat to downstream communities or infrastructure was assessed, and found that our results were broadly consistent with those previous studies (Table 4.3). This is encouraging because our risk assessment model has been applied here to a range of regions and dam-types, whereas previous studies have generally focused on specific regions or specific lake or dam contexts. This widely applicable assessment is useful from a risk-management perspective because many glacierised landscapes contain a range of glacial lake types, and our model allows all lakes to be evaluated simultaneously. Specifically, the same results for Lake Hanpi K'ocha as did Frey et al. (2016) were achieved, even though their risk assessment was based on field study and the use of criteria that cannot be evaluated in a desk-based study. Allen et al. (2009) focused only on hazard analysis rather than risk or impact assessment, but their outburst flood modelling results for Maud Lake and Godley Lake do not show any potential downstream impacts, which is consistent with the low risk rating from our MCDA method. Aggarwal et al. (2017) estimated Chholamo to represent a low GLOF susceptibility and Lake 0071 to represent a medium GLOF susceptibility, but both of those lakes are not upstream of important infrastructure or population, and hence are rated as low risk in our assessment. Worni et al. (2013) estimated that Gopang Gath and Spong Tongpo pose a medium level of risk, which agrees with our results. This is due mostly to the relatively low downstream population and the long runout distances required for flood impact to villages. In addition, triggering factors (TR.1, 2, 3) are graded as low in this area of the Himalaya. Worni et al. (2013) also assessed Schako Tsho and found that it posed a high level of risk, which agrees with our results. This rating is driven by intense precipitation events, steep slopes in close proximity to the lake, and the presence of nearby communities downstream. Rounce et al. (2016) assessed eight large Nepalese lakes with significant populations or infrastructure downstream. All eight lakes are in close proximity to steep slopes, most are in contact with parent glaciers, and there are potential triggers including seismic activity and intense precipitation events. The authors assessed the GLOF risk of most lakes to be high, with the exception of Imja Tsho, which was graded as medium risk, and Lower Barung Tsho, which was graded as very high risk. The authors underline that Imja Tsho will become high risk in the next 10 to 20 years because it is growing rapidly. Our model largely agrees with these results by classifying all of these lakes as high risk.

4.4.2 Comparisons of model results with GLOF-generating lakes

Table 4.3 also presents pre-GLOF risk assessments for seven lakes that have already generated GLOFs. This selection of GLOF-generating lakes comprises a mixture of ice, moraine and bedrock dams located in different regions around the world. Flatbreen lake burst in 2004 and generated a debris flow that reached the valley bottom ~1000m below the lake (Breien et al., 2008). This lake is graded as low risk (a result that is sustained throughout the sensitivity analyses – Tables 4 and 5) due to both downstream impact parameters (IM.1 and IM.2) falling into the low impact category - there is no significant population or infrastructure in the immediate floodpath downstream (except farmland and a minor road). The Passu lake, Keara lake and lake

513 GLOF events are known to have damaged roads or bridges, or to have increased downstream sedimentation causing malfunction of water-treatment plants or damage to agricultural land (Ashraf et al., 2012; Carey et al., 2012; Hoffmann and Wegenmann, 2013; Klimeš et al., 2014; Vilímek et al., 2015). Nevertheless, they did not cause any casualties or fatalities. These factors are key drivers of the medium-risk classification from our MCDA method (Table 4.3). In contrast, Halji and Chorabari lakes are situated in relatively close proximity to downstream infrastructure and relatively high population numbers meaning that the overall risk was graded as high.

4.4.3 Potentially dangerous glacial lakes of the Bolivian Andes

GLOF risk was assessed for 25 lakes in the Bolivian Andes (Table 4.6). This represents the sort of situation where our model would be particularly valuable, i.e. in a region where GLOF risk has not yet been studied in detail, there are a range of lake types that need to be assessed simultaneously, and there are few data or observations to base decisions upon.

Our MCDA method reveals that 22 lakes represent low risk, mostly because of the low levels of downstream population and infrastructure, as well as the presence of bedrock dams, which are regarded as being more stable, and small estimated lake volumes. In addition, the glacierised area of the Cordillera Oriental, where these lakes are situated, is not a highly seismically active zone. Nevertheless, three lakes pose a more significant potential threat to downstream areas: the lake situated upstream from the village of Pelechuco, as well as Laguna Glaciar and Laguna Arkhata. Pelechuco lake and Laguna Glaciar are classified in our model as medium risk lakes with a high level of confidence, as shown in Table 4.6 (0.84 and 0.81 respectively). This can be explained by the high population downstream, and both seem to be susceptible to GLOFs since they are in contact with their parent glacier, and surrounded by steep slopes. Laguna Arkhata is the only lake classified as high risk, with a confidence level of 0.58. This is mostly due to its large size, the large population downstream, steep slopes surrounding the lake, and contact between the lake and parent glacier. Having completed the MCDA method, future work can now be directed more confidently toward intensive study of the three most dangerous lakes.

4.4.4 MCDA model sensitivity

To our knowledge, the first sensitivity analysis of any GLOF risk or hazard assessment model was undertaken. Sensitivity analysis allows the strength of the model to be assessed, and the certainty of lake risk classification to be explored. Sensitivity analysis is readily undertaken in the SMAA-TRI software, which is a key benefit of our approach.

All medium and high-risk lakes have at least three criteria rated as high risk (except Gopang Gath, which possesses only two high risk criteria), which causes them to remain in or switch into a high-risk category when the cutting level is increased from 0.65 to 0.85 (Table 4.4). Low-risk lakes and Gopang Gath stand out in Table 4.4 because their risk classification remains stable for all or most of the sensitivity tests. All low-risk lakes are dominated by low-risk ratings for all criteria so that even as the λ-cutting level is increased (i.e. the model is made more conservative), their overall risk level remains low. Gopang Gath, on the other hand, has a high number (9 out of 13) of criteria rated as medium risk, and only two high risk and two low-risk criteria. Therefore, the lake has an overall rating of medium risk until the cutting level is raised to 0.85, where even then the high-risk classification has only a modest confidence value of 0.44 (with low risk at 0.28 and medium risk at 0.28) (Table 4.5). Crucially, sensitivity analysis can be used, as it is here, to identify those lakes that remain within the same risk class as the cutting level is increased, which gives confidence to the user in making risk management decisions (e.g. whether additional monitoring or remediation would be required), or to identify cases where lakes are close to a higher risk boundary after the initial assessment with a lower cutting level (i.e. lakes that switch class as the cutting level is increased), and to evaluate the confidence level of the risk classifications. Overall, a λ-cutting level of 0.65 should be sufficiently robust for general use or initial risk assessment.

One of the key benefits of the MCDA approach is the use of the Description Problem approach to decide upon appropriate GLOF risk assessment criteria. However, the choice of thresholds for each criterion remains uncertain in some cases (see also Supplementary Data - Appendix 4.1). Hence, the effect of changing the threshold values for the high-risk category of each criterion was also explored (Table 4.5). For the most part, Table 4.5 illustrates that alteration of the thresholds for most criteria yields relatively few changes in risk categorization for each lake in our sample. This is due in large part to the fact that many of the lakes in our sample already fall into the high-risk category for each criterion, meaning that a relaxation of the criteria for high risk has little effect on the results. Nevertheless, there are a few notable exceptions. By relaxing the seismic activity (TR.1) high-risk threshold, 4 lakes are re-graded as high risk. However, this probably constitutes an unrealistic reclassification whereby mountain ranges with modest or low seismic activity are ascribed a higher risk rating. Risk managers and geoscientists should be able to gain sufficiently accurate information on regional seismic activity that they can attain appropriate thresholds and classifications, and the sensitivity analysis here gives us greater confidence that our original risk thresholds were already robust and realistic. Another exception is lake volume (SR.2) where the relaxation of the high-risk threshold results in three lakes being re-graded as high risk. Lake volume is an example of a criterion where it can be hard to determine where the thresholds should lie – in essence, it is hard to say what constitutes a large, medium or small lake. Our original lake volume classification (Table 4.2) is derived from a global glacial lake dataset (Cook and Quincey, 2015) that includes water bodies ranging in size from supraglacial ponds (0.1 x 10^6 m^3) to very large lakes (770 x 10^6 m^3) (see also Supplementary Data - Appendix 4.1). Our thresholds were informed by plotting a frequency distribution of the dataset presented in Cook and Quincey (2015). By relaxing the high-risk threshold, any lake with a size of 1 x 10^6 m^3 or larger is classified as high risk, which captures most of the lakes in our sample set. Given that the lake might not drain completely during a GLOF event, this revised threshold might be regarded as being overly conservative. Again, our sensitivity analysis gives us confidence that our original threshold was appropriate. Finally, relaxation of the GLOF travel distance high-risk threshold (SR.1) also causes three lakes to be re-graded as high risk. Our original threshold system was informed by previous studies (Huggel et al., 2002; Huggel and Hegglin, 2008) that adopted an empirical approach to defining the critical slope for clear water and debris-laden GLOF runout. Given this empirical basis, our sensitivity analysis here merely explores a very conservative threshold system, although risk managers may wish to use this system if there are large uncertainties about topography or the nature of the potential flood (e.g. whether sediment is likely to be entrained into a debris flow).

A small number of lakes, including Lake 513 and Passu Lake, are readily reclassified when the high-risk threshold is relaxed for some criteria (including TR.1, ME.3, SR.1, SR.2, IM.1). These lakes may need particular attention from risk managers, as they appear to be borderline cases. Fortunately, sensitivity analysis is able to reveal such cases.

4.4.5 The use of MCDA in GLOF risk assessments

Several previous studies (Huggel et al., 2004; Bolch et al., 2008; Mergili and Schneider, 2011; Emmer and Vilimek, 2013; Worni et al., 2013; Rounce et al., 2016) have provided important frameworks by which to assess GLOF hazard or risk. Since these are typically designed for particular sites or regions, and/or for specific lake types, they are already likely to provide robust risk and hazard assessments in those situations. However, risk managers in some regions may be presented with situations where a range of lake types may exist, and it is desirable to assess the relative level of hazard or risk between these lakes simultaneously. For example, a risk or hazard assessment designed for moraine-dammed lakes cannot necessarily be used to assess the risk or threat posed by ice-dammed or bedrock-dammed lakes. In this study, an MCDA approach that offers several key benefits for GLOF hazard and risk assessment was presented, that make it particularly useful in such situations. In common with some, but not all, previous studies (Fujita et al., 2008; Bolch et al., 2011; Aggarwal et al., 2016; Petrov et al., 2017), our MCDA approach uses free and widely available datasets or inputs, and there is no need for the inclusion of any field data – all of the information can be gathered and processed remotely as a desk-based study. Certainly, additional field-based data or higher resolution satellite imagery or elevation data would be advantageous, and could be incorporated into the MCDA model, but it was shown here, through comparisons with previous studies and sensitivity analyses, that this approach is already robust. Our approach would be particularly useful in serving as an initial survey for an area with several lake types in order to identify particularly dangerous lakes that might require further detailed study (e.g. fieldwork, hydrological modelling, remediation, monitoring, etc.). The MCDA approach presented here is a two-stage process, whereby a Description Problem is addressed first, before a Sorting Problem is completed. The formulation of the Description Problem represents another key benefit compared to previous GLOF risk and hazard assessments. Firstly, and in common with some previous reviews on GLOF initiation and impacts (e.g. Emmer and Vilimek, 2013;

Rounce et al., 2016), it forces a comprehensive review of all factors that could drive a glacial lake towards becoming dangerous (Fig. 1 and Tables 1 and 2). Crucially, however, the principles of MCDA (section 2.1) mean that the criteria selected to assess GLOF risk are exhaustive, non-redundant, and consistent. Many previous studies have kept, for example, one composite criterion instead of splitting it into multiple criteria, therefore potentially biasing the analysis.

The use of the SMAA-TRI software has some specific advantages. Firstly, it is freely available, but it is also straightforward to use, and it has a means of testing the strength of results through the generation of confidence measures and sensitivity analyses, as outlined in this study. Further, although a Sorting Problem approach was followed, the use of SMAA-2 (which can be found in the same download package; http://smaa.fi/) allows the construction of a Ranking Problem, which may be useful for other practitioners with different requirements.

Our MCDA approach, through the construction of a Description Problem (section 2.2), streamlines the wide array of criteria that have been used previously to assess GLOF risk. Nonetheless, since our approach offers a rapid, first pass assessment of GLOF risk, the final 13 criteria used inevitably ignore some criteria that cannot be assessed remotely (e.g. vulnerability factors, specific details about the nature of the dam, etc.). Hence, there remain situations where it would be advantageous to use existing GLOF risk assessments that have been tailored to specific lakes, regions or contexts, or where field data are available to be incorporated into the risk assessment to address particular criteria.

There remain a number of challenges for those constructing and using GLOF risk and hazard assessments. Firstly, the thresholds used to define risk categories are uncertain. For the most part, thresholds for each criterion were borrowed based on previous work (see also Supplementary Data - Appendix 4.1), and this then reflects some degree of consensus among the GLOF risk community about how to assess GLOF risk. But some values might be questioned. For example, how big is a big (high-risk) lake? How steep is a steep (high-risk) slope that could shed ice or rock mass movements into the lake? Should potential loss of life thresholds that could be applicable to mass casualty events, such as tsunamis and earthquakes be used, where many thousands of people could lose their lives, or should lower thresholds considering that most GLOF-affected environments are relatively sparsely populated be used? Another unsolved problem is the weighting for each of the criteria used. At this stage, it is impossible to tell whether some criteria are more important than others, with the exception perhaps of loss of life and damage to infrastructure.

4.5 Conclusion

For the first time, a risk assessment for glacial lake outburst floods (GLOFs) using a Multi-Criteria Decision Analysis (MCDA) approach was undertaken. MCDA has been applied to several natural hazard and risk contexts, but never before to GLOFs. Whilst several previous studies have outlined GLOF hazard and risk assessment procedures, it is argued here that the MCDA method has a number of benefits to offer. The MCDA approach (1) uses freely and widely available data inputs and software, without the requirement for field-based study; (2) can be applied across a range of glacial lake contexts (ice-dammed, moraine-dammed, etc.) simultaneously, and to any region of the world; (3) enables researchers to make a first-pass analysis of potentially dangerous lakes objectively before committing to further investigation (e.g. field work, remote sensing data analysis); and (4) readily permits sensitivity testing of the model. Crucially, the first stage of the MCDA approach (the Description Problem) involves the determination of appropriate criteria by which to define risk. The principles of MCDA require the use of exhaustive, non-redundant, and consistent criteria, which can be regarded as a key benefit of this approach. For example, previous assessment procedures have sometimes double-counted, ignored, or selected criteria subjectively or non-transparently (McKillop and Clague, 2007a,b).

The risk of 16 potentially dangerous glacial lakes as well as 6 lakes that have already generated GLOFs in the past (between 2004 and 2013) was assessed. Our results for the 16 extant lakes compare favourably with previous risk and hazard assessments, which have generally focused on specific regions or glacial lake contexts. This indicates that our MCDA model can be applied in a range of contexts globally. Further, sensitivity analyses of our model was undertaken to explore the robustness of results and model assumptions. To our knowledge, this is the first time sensitivity analysis has been performed for a GLOF risk or hazard assessment model. Two sensitivity analyses were undertaken. In the first, the proportion of criteria that need to be graded as 'high risk' in order to grade the overall risk as 'high' was relaxed (the so-called 'λ-cutting level'). This identified several lakes that remain within the same risk class as this cutting level is increased, which gives confidence to the user in making risk management decisions about those lakes. The second sensitivity test involved relaxing the threshold for 'high risk' for each criterion. This generally revealed that the original risk thresholds used here were robust, although some lakes were identified that might warrant further study because they changed readily to a higher risk class. The tested method was applied on 25 glacial lakes in the data-scarce Bolivian Andes, and found that 22 of these lakes represent low risk, and therefore do not currently require further attention. Nevertheless, further detailed investigation or action is required for two lakes rated as medium risk (Pelechuco, Laguna Glaciar), and one lake rated as high risk (Laguna Arkhata).

It is suggested that our MCDA approach would be best suited to identifying potentially dangerous lakes in regions where a range of glacial lake types may exist, such as demonstrated here for the Bolivian Andes. Our method allows the relative risk of these different lakes to be assessed simultaneously, and takes account of both GLOF susceptibility and potential impacts.

Next, Chapter 5 will focus on the application of hydraulic modelling to the two medium-risk and the one high-risk lakes in order to observe in detail the level of impact on local population.

Chapter 5

Modelling glacial lake outburst flood impacts in the Bolivian Andes

(Chapter published - see Appendix 1.2)

5.1 Introduction

The previous Chapter (4) focused on GLOF risk in Bolivia, a matter that has received very little attention despite an event having occurred here in 2009, when an ice-dammed lake drained catastrophically, impacting the village of Keara in the Cordillera Apolobamba (Hoffmann and Wegenmann, 2013). A GLOF risk assessment technique was developed based on the use of multi-criteria decision analysis (MCDA), which was applied to the lake inventory of Cook et al. (2016). It was demonstrated that from the 25 potentially dangerous Bolivian lakes, two lakes represented 'medium' risk and one lake represented 'high' risk. In this study, the aim is to model potential GLOF inundation downstream from these three lakes, and assess the possible impacts on downstream communities and infrastructure.

5.2 Geographical setting and methods

5.1.1 Geographical setting

This study focused on the glaciated ranges of the Cordillera Oriental, Bolivia; from north to south these are the Cordillera Apolobamba, the Cordillera Real (including Huayna Potosí, Mururata, Illimani), and the Cordillera Tres Cruzes (Fig. 5.1). The three lakes identified by Kougkoulos et al. (2018) as having the highest risk include Laguna Arkhata, Pelechuco Lake, and Laguna Glaciar (Fig. 5.1). The only documented GLOF in Bolivia occurred at Keara (Fig. 5.1), which serves as a test case for our modelling approach. The Keara GLOF took place on November 3rd 2009 at about 11:00 a.m. local time, and involved the complete drainage of an ice-dammed lake (Hoffmann and Weggenmann 2013). This event flooded cultivated fields, destroyed several kilometres of a local dirt road, washed away pedestrian bridges, and killed a number of farm animals (Hoffmann and Weggenmann 2013). Fortunately, there were no human fatalities.

Information about the lakes discussed in this study (e.g. coordinates, measured areas, estimated volumes) is presented in Table 5.1. The lakes exist in the same region (Cordillera Oriental), and so are subject to similar environmental conditions (e.g. regional seismic activity, intense precipitation events, high temperature events). However, these lakes were found by Kougkoulos et al. (2018) to be more susceptible than other glacial lakes in the region because of local conditions that control potential

GLOF triggering mechanisms. Some information about these potential triggers is provided in the subsequent sub-sections.

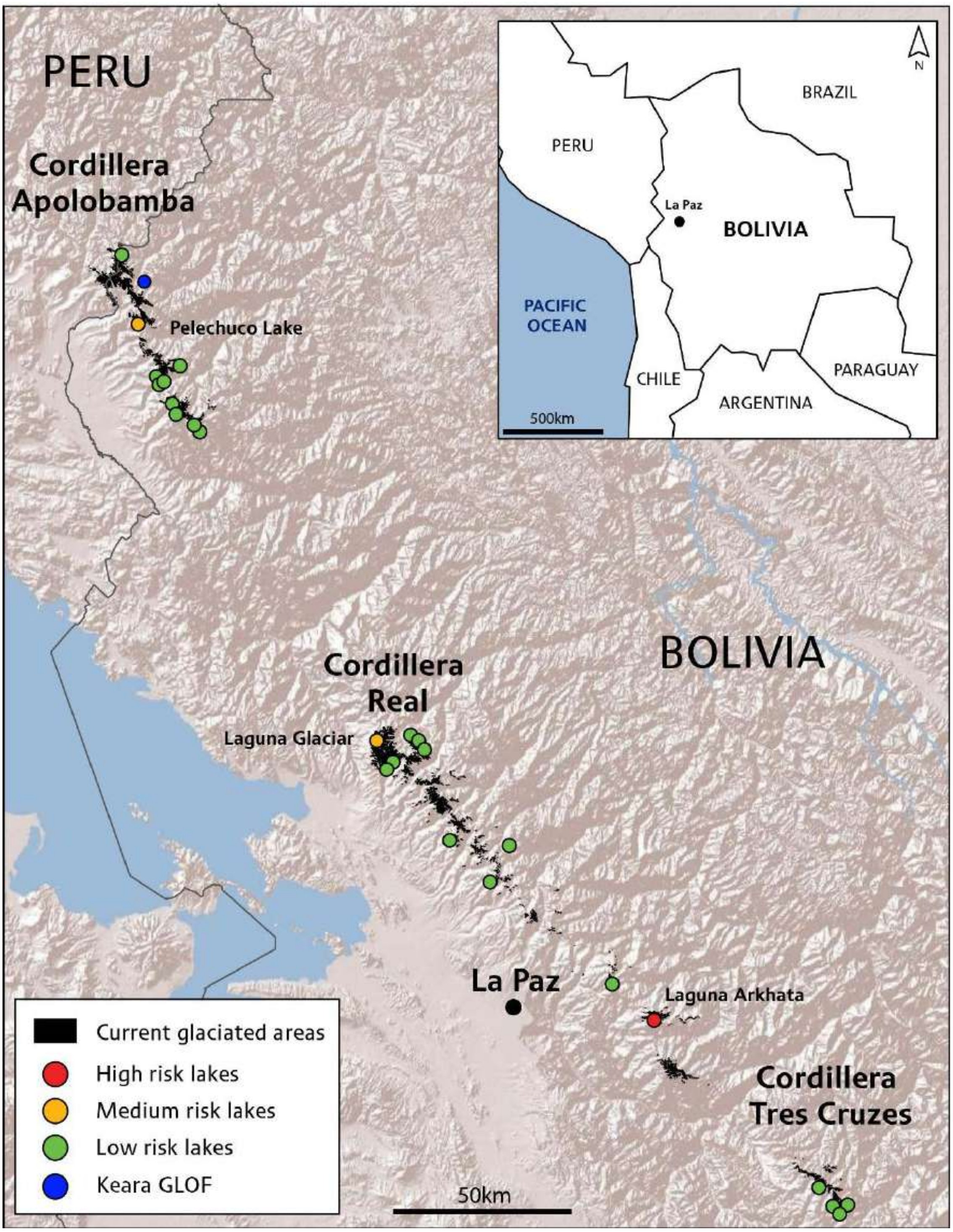


Fig. 5.1. Location of glaciers and potentially dangerous glacial lakes in the Bolivian Andes, as well as the 2009 Keara GLOF event. The risk of each glacial lake identified by Cook et al. (2016) was assessed by Kougkoulos et al. (2018) using the MCDA methodology; three lakes were graded as 'medium' (orange) and 'high' risk (red), and form the focus of this study

Table 5.1. Parameter values used for the three different scenario simulations in HEC-RAS. To estimate Qmax for the Keara Lake, Walder and Costa equation for non-tunnel floods (1996) was used. Evans (1986) was used for the remaining three lakes. Drainage percentage remains at 100% in Keara because the entire lake drained during the 2009 GLOF event.

Lake (coordinates in UTM)	Scenario	Outburst duration (s)	Manning's value	Lake area (m^2)	Estimated lake depth (m)	Lake volume (m^3)	Drainage percentage (%)	Total discharge volume (m^3)	Q_{max} ($m^3 s^{-1}$)
Keara Lake (19L 481958 8377253)	Optimistic	1000	0.05	34000	4	136783	100	136783	458
	Intermediate	1500	0.04		8	261088	100	261088	609
	Pessimistic	2000	0.03		11	385394	100	385394	723
Pelechuco Lake (19L 481205 8365591)	Optimistic	1000	0.05	80000	12	996890	20	199378	464
	Intermediate	1500	0.04		15	1209618	50	604809	835
	Pessimistic	2000	0.03		18	1422346	100	1422346	1313
Laguna Glaciar (19L 5470858249728)	Optimistic	1000	0.05	328600	19	6382045	20	1276409	1240
	Intermediate	1500	0.04		23	7500896	50	3750448	2196
	Pessimistic	2000	0.03		26	8619746	100	8619746	3413
Laguna Arkhata (19K 624521 8172040)	Optimistic	1000	0.05	699200	30	20835270	20	4167054	2322
	Intermediate	1500	0.04		34	23993347	50	11996674	4067
	Pessimistic	2000	0.03		39	27151425	100	27151425	6270

5.1.1.1 Pelechuco Lake

Pelechuco lake is located in the Cordillera Apolobamba (Fig. 5.1) and, according to Kougkoulos et al. (2018), is considered as medium GLOF risk. This is due to the lake being in contact with steep (> 45°) surrounding slopes that could generate avalanches and/or rockfalls, which in turn could impact the lake and generate a displacement wave; this is the most common GLOF triggering mechanism in three different regions (Cordillera Blanca, North American Cordillera, Himalaya) (Emmer and Cochachin, 2013). Further, the parent glacier is also in proximity (<200 m) to the lake head, raising the possibility of ice calving into the lake, also generating a displacement wave.

5.1.1.2 Laguna Glaciar

Laguna Glaciar is located in the Cordillera Real (Fig. 5.1). According to Kougkoulos et al. (2018), this is considered a medium risk lake due to a visibly low dam freeboard (< 5m), as well as the lake being in contact with the retreating parent glacier, which could calve into the lake. The surrounding steep slopes (30-45°) also raise the possibility of avalanches and/or rockfalls impacting the lake.

5.1.1.3 Laguna Arkhata

Laguna Arkhata is located in the Cordillera Tres Cruzes (Fig. 5.1). According to Kougkoulos et al. (2018), it is considered the highest risk lake. This is mostly due to the steepest slope (> 45°) surrounding the lake, capable of shedding avalanches and/or rockfalls into the lake, as well as the lake being in contact with the retreating parent glacier, which could calve into the lake. Specifically there are numerous steep, hanging areas of glacier ice above the lake.

5.1.2 Topographic data acquisition

Topographic data are central to the modelling of flood inundation. For each lake, DEMs from stereo and tri-stereo SPOT 6/7 satellite imagery (1.5 m horizontal resolution) were generated using the DEM extraction module in ENVI (version 5.3) (Table 5.2). For each of the four lakes and their GLOF runout zones, at least two of the following types of image angles were obtained: one forward-looking (F), one nadir-looking (N) and one backward-looking (B) (Table 5.2). Images with across-track angles of between -15 and +15 degrees were acquired. For each of the three lakes and potential GLOF runout zones, approximately thirty tie points were identified over the pairs of images used for each DEM in order to calculate shift parameters between images at each tie point, obtaining an overall root-mean-square error (RMSE) of less than 1 pixel (<1.5 m). In areas where there is a lack of field GPS data, some studies suggest the use of Google Earth for obtaining Ground Control Points (GCPs) (Watson et al. 2015). Therefore, 15 GCPs were collected for each set of images. The combination of FNB images produced a 1.5 m resolution DEM for each site. The DEMs were resampled to 2 m spatial resolution in order to eliminate artificial roughness due to the stereo processing technique (Kropáček et al. 2015).

An ASTER GDEM V2 with a 30 m horizontal resolution was also acquired because, in Agua Blanca, a community situated downstream of Pelechuco lake, our SPOT-derived 2 m DEM contains a gap due to terrain shading. For this small area the ASTER GDEM was used instead. The ASTER GDEM has been used in several GLOF modelling studies (e.g. Gichamo et al. 2012; Wang et al. 2012; Watson et al. 2015) because it is free to download, and covers most of the Earth's landmass. In other cases, the DEM resolution has been resampled into a higher resolution in order to enable a higher level of precision in GLOF modelling, although the underlying DEM accuracy is not improved (e.g. Bajracharya et al. 2007; Allen et al. 2009; Rounce et al. 2016). In this study, a hydrological correction by filling sinks on both high (SPOT 2 m) and low (ASTER GDEM 30 m) resolution DEMs was also applied.

Table 5.2. Satellite images used for DEM extraction.

Sensor	Product	Satellite	Resolution	Scene ID number	Date	Time	Incidence Angle (Across Track)	Cloud cover (%)	Lake
SPOT	TRI-STEREO	6	1.5m	201308011418261	8/1/2015	14:18:37	10.1	2.3	Arkhata
				201308011419035		14:19:14	6.1	1.4	
				201308011418447		14:18:56	7.4	1.5	
SPOT	MONO	6	1.5m	201507091429124	7/9/2015	14:29:45	-11.2	1.1	Glaciar
SPOT	MONO	6	1.5m	201304241430052	4/24/2015	14:30:27	-6.9	28.8	
SPOT	MONO	6	1.5m	201306291422166	6/29/2013	14:22:33	16.0	0	Pelechuco, Keara
SPOT	MONO	6	1.5m	201307111430521	7/11/2013	14:31:05	-14.9	3.2	
SPOT	MONO	7	1.5m	201507291425516	7/29/2015	14:26:08	-0.5	7.6	

5.1.3 Estimating lake volume

Lake volume defines the maximum amount of water that could be involved in a GLOF. Since bathymetric data were unavailable for the lakes examined in this study, lake volume had to be estimatedusing lake area measured from satellite imagery and a mean depth based on empirical equations. Specifically, Cook and Quincey (2015) found that the relationship between lake area, depth and volume varied depending on the geomorphological context of the lake. Using the empirical dataset compiled by Cook and Quincey (2015), the mean depth (*Dm*) of ice-dammed lakes (i.e. Keara in this study) is predicted by the equation:

$$\mathrm{Dm} = 1 \times 10^{-5}\,\mathrm{A} + 7.3051 \tag{5.1}$$

Where A is lake area. This relationship yields an R^2 value of 0.90 and a P-value <0.0001 (Appendix 5.1).

The mean depth of moraine-dammed lakes (i.e. Pelechuco and Laguna Glaciar in this study) is predicted by the equation:

$$\mathrm{Dm} = 3 \times 10^{-5}\,\mathrm{A} + 12.64 \tag{5.2}$$

This relationship yields an R^2 value of 0.83 and a P-value <0.0001 (Appendix 5.1).

Laguna Arkhata is bedrock-dammed, but as yet there are no depth-area relationships that exist for such lakes. Therefore, lake depth for Laguna Arkhata was calculated using equation 2.

The errors on the constants within each of the two linear regression models were calculated in Equations 1 and 2 (at a confidence level of 95 %) and were applied to determine a range of lake depths for the three lakes under investigation (Appendix 5.1, Table 5.1). Lake volume (V) was estimated by multiplying the measured lake area (in Google Earth Pro) by the derived lake depth from Equation 1 or 2, and the errors associated with lake volume were estimated by propagating the errors associated with lake depth.

5.1.4 Estimating peak discharge

Several empirical equations have been applied in the past to estimate peak discharge from natural-dam (e.g. moraine, bedrock) failures (see Table 3 in Westoby et al., 2014a). These relationships require inputs such as lake area, lake volume, water depth at dam, dam height, etc. (e.g. Riggs 1976; Williams 1978; Froehlich 1995; Pierce et al. 2010). Some of these parameters can be assessed remotely (e.g. from satellite imagery or DEMs), whereas others require field investigation. For simplicity, the use of two commonly employed relationships was chosen to model peak discharge from ice-dammed and moraine-dammed lakes. The equation of Walder and Costa (1996) for non-tunnel floods was used to model peak discharge (Q_{max}) of the ice-dammed lake failure at Keara, which was the test case for our hydrodynamic modelling (see below).

$$Q_{\mathrm{max}} = 1100 \times (V/10^6)^{0.44} \tag{5.3}$$

The relationship of Evans (1986) was used for the potentially dangerous moraine-dammed lakes of Pelechuco and Laguna Glaciar, as well as the bedrock-dammed Laguna Arkhata:

$$Q_{\mathrm{max}} = 0.72V^{0.53} \tag{5.4}$$

All pro-glacial lake size estimations (e.g. area, depth, volume) can be found in Table 5.1.

5.1.5 Dam breach hydrograph and modelling parameters

Numerous parameters (e.g. peak discharge, sediment load, channel roughness) can modify the flood inundation and flow behaviour of a simulated flood, leading to uncertainty in flood modelling and risk assessment (Anacona et al. 2015; Wang et al. 2015b; Kropáček et al. 2015). Table 5.1 presents a summary of the modelling scenarios undertaken, together with the accompanying values for each model parameter (i.e. lake volume, percentage of lake drainage, outburst duration, Manning's value, peak discharge). Each of these parameters were discussed in turn.

Fujita et al. (2013) was followed in calculating potential flood volume (PFV) as the product of lake area and either the mean depth (*Dm*), or the potential lowering height (*Hp*); Fujita et al. (2013) recommend using the lower of these two values to calculate PFV. Values for *Dm* (Section 2.3; Table 5.1) were compared against those calculated for *Hp*. *Hp* is the amount of lake lowering expected during a GLOF assuming that, after GLOF initiation, incision into the moraine dam will proceed until the angle between the lake and the downstream area is lowered to 10° (termed the 'depression angle'). Depression angle maps were created (Appendix 5.2), and mapped the steep lakefront area (SLA) 1km downstream of each lake, following Fujita et al. (2013), in order to calculate *Hp* (see Appendix 5.2). In all cases, the value of *Dm* is lower than that calculated for *Hp*, and so *Dm* is used in the calculation of lake volume.

The volume of water drained from the lake is highly uncertain principally because this will be determined by the triggering mechanism, which could vary in nature and severity, and the resilience and integrity of the impounding dam. Hence, three different drainage volumes were modelled, which represent optimistic, intermediate, and pessimistic scenarios. Different values for the extent of lake drainage were defined, ranging from 20 % of the lake volume for the optimistic scenario, 50 % for intermediate, and 100 % for the pessimistic scenario. These scenarios are guided by previous work on GLOF drainage volumes. For example, Anacona et al. (2014) studied 14 Patagonian moraine-dammed lakes before and after GLOF events and found that two lakes emptied entirely (100 % drainage), four emptied by more than 50 %, two by around 50 %, and six lakes generated smaller outbursts with less than 20 % drainage. In another study, Kropáček et al. (2015) modelled 125 % lake drainage for their worst-case (pessimistic) scenario, with the additional 25 % drainage accounting for possible future lake expansion in response to continued glacier recession. However, all lakes in our study are already at or very close to their maximum filling capacity, and so it is not necessary to model larger lakes. The lake drainage value for Keara was set to 100 % since the observational evidence indicates that the lake drained completely (Hoffmann and Wegenmann 2013). For the other three lakes, it is unlikely that they would drain completely, but the 100 % drainage scenario as the worst possible case was used.

Previous studies have recommended a flood duration of between 1000 to 2000 seconds based on empirical data from the Swiss Alps (Haeberli 1983; Huggel et al. 2002). Therefore, 1000 s and 2000 s were used as outburst duration for the pessimistic and optimistic scenarios respectively, and 1500 s for the intermediate scenario. As Worni et al. (2012) and Westoby et al. (2014a) suggest, if there are no data on lake outflow duration and lake discharge, the outflow hydrograph can only be validated indirectly (e.g. with the Keara event as a validation point in this case). Although simulations of drainage duration can be tuned to fit an observed hydrograph, hydrograph forecasting is difficult because non-linear flood physics make drainage duration sensitive to the initial conditions (Ng and Björnsson 2003), which are usually uncertain. All three of our potentially dangerous glacial lakes are either bedrock- or moraine-dammed, so it was assumed that flood discharge would increase linearly to a peak, after which it decreases linearly to 0 m^3/s over a time span equal to that of the rising limb; in other words, hydrographs were assumed to be triangular in shape as has been applied in previous GLOF modelling studies (Anacona et al. 2015; Kropáček et al. 2015; Somos-Valenzuela et al. 2015; Wang et al. 2015b) (Fig. 5.2). Some previous studies have considered that the higher the peak discharge, the longer the flood duration (Anacona et al. 2015; Wang et al. 2015b), whereas others assume a shorter flood duration for a higher peak discharge (Somos-Valenzuela et al. 2015). The latter option will be used such that our worst case pessimistic scenario has the highest peak discharge and shortest flood duration, and the optimistic scenario has the lowest peak discharge and longest flood duration. Ice-dammed lake failures usually generate flood hydrographs with a relatively slow, exponentially rising limb, and a rapidly falling limb (Kingslake 2013). Nevertheless, a triangular-shaped hydrograph for the Keara ice-dam breach was used, because no detailed data were available concerning the event, and comparison can take place more readily with results from the three lakes that are yet to generate GLOFs.

In-channel and floodplain Manning's values for each scenario were set to represent mountain streams without vegetation (Table 5.1), although the type of terrain could only be defined by performing an inspection on Google Earth and from our own fieldwork observations at Pelechuco, in the Cordillera Apolobamba.

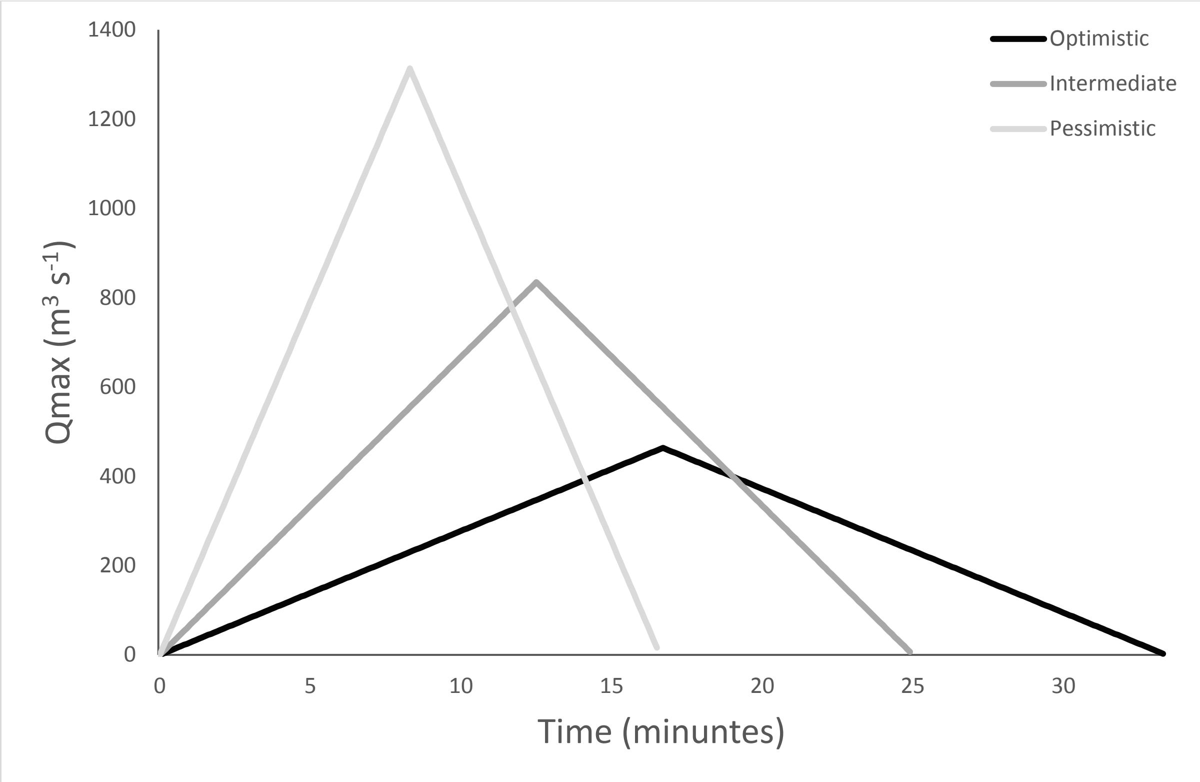


Fig. 5.2. Example breach hydrograph for Pelechuco lake illustrating all three scenarios for a potential GLOF (optimistic, intermediate and pessimistic). The same hydrograph shapes are used for all three lakes.

5.1.6 Hydrodynamic modelling of GLOFs

Modelling of GLOF hazard and risk has been undertaken in several regions around the world, using a variety of different approaches. Some studies have used simple geometric models such as the Modified Single Flow (MSF) (Huggel et al., 2002; Allen et al., 2009; Prakash and Nagarajan, 2017), the random walk process (Mergili and Schneider, 2011), or the Monte Carlo Least Cost Path (MC-LCP) (Watson et al., 2015; Rounce et al., 2016, 2017) to make a rapid assessment of potential flood inundation. Such models require very little input data and can be applied to many lakes, but serve as a first-order assessment that cannot go as far as to produce realistic flood maps. Other studies have focused on more detailed modelling approaches using HEC-RAS 1D (Bajracharya et al., 2007; Dortch et al., 2011; Klimeš et al., 2014; Watson et al., 2015), HEC-RAS 2D (Anacona et al., 2015; Wang et al., 2015), FLO 2D (Petrakov et al., 2012;

Somos-Valenzuela et al., 2015), and BASEMENT (Worni et al., 2012, 2013; Somos-Valenzuela et al., 2016), all of which require further data such as channel bed roughness, and the volume of water that could drain from the lake. These techniques are capable of generating inundation maps (area affected, run-out distance, and depth of flow) that can be used to inform risk management and mitigation strategies.

Here, GLOFs were modelled (inundation area, arrival time, depth and velocity) using the 2D US Army Corp of Engineers model, HEC-RAS 5.0.3 (http://www.hec.usace.army.mil/). HEC-RAS was used because it is downloadable free-of-charge, and has been employed successfully to model GLOF inundation in a number of previous studies (e.g. Bajracharya et al., 2007; Dortch et al., 2011; Klimeš et al., 2014; Anacona et al., 2015; Wang et al., 2015; Watson et al., 2015). The 2D version of this model can simulate multi-directional and multi-channel flows, which are characteristic of GLOFs (Westoby et al. 2014a, 2014b; Wang et al. 2015b; Watson et al. 2015). The model setup included the definition of upstream and downstream boundary conditions, the creation of a grid with elevation data, the selection of Manning's roughness values, slope parameters, and the model spatial domain. The unsteady flow simulation was performed for all four Bolivian GLOF case studies in order to observe: (1) peak flow propagation, (2) flood inundation extent, and (3) the flood water depth.

Our simulated dam-breach hydrographs for the upstream boundary condition of each model was used (see section 2.5 for more details). The normal depth option was used for the downstream boundary condition. This latter option uses Manning's equation to estimate a stage for each computed flow. To use this method, the user is required to enter a friction slope for the reach close to the boundary condition. If no detailed data exist, the slope of water surface can be used as a good estimate for the friction slope (Brunner 2010). This type of boundary condition should be placed far enough downstream of the study reach (i.e. potentially impacted communities) such that any errors it produces will not affect the results of the GLOF runout area (Brunner 2010; Watson et al. 2015). Hence, the boundary was placed 2 km downstream of the last community potentially affected by a GLOF from each lake. In addition, even though HEC-RAS has the ability to simulate debris-flows, GLOFs were simulated as clear-water flows due to a lack of information about the nature of stream beds. It is acknowledged here that GLOFs are very likely to erode and entrain debris as they propagate downstream, and possibly evolve into debris flows, although many other studies also model GLOFs as clear-water flows due to data constraints (e.g. Anacona et al. 2015; Kropáček et al. 2015; Wang et al. 2015b; Watson et al. 2015).

Our overall approach was to test the model against field observations of the 2009 Keara event to ensure that realistic flood depths and inundation extent was achieved. The same modelling methodology was then applied to the three potentially dangerous lakes identified by Kougkoulos et al. (2018).

5.1.7 Population and infrastructure data

Population and infrastructure data are required to assess potential GLOF impacts. These data were acquired from the GeoBolivia portal (http://geo.gob.bo/portal/), which offers open access to the 2012 population census and infrastructure data of the Bolivian National Statistical Institute. To quantify the downstream impacts, the number of buildings affected by the flood were manually counted. For each community, the total population of the community was divided by the number of buildings in the community to estimate the number of people per building. This enabled us to estimate the number of people impacted by the flood. However, it is acknowledged that there are likely to be spatial differences in population within each community, and, because of seasonal migration within Bolivia (Oxfam 2009), there will be temporal population variations (which were not considered further in this study).

Field observations in the Cordillera Apolobamba region in July 2015 demonstrate that building structures are usually single storey residential dwellings made of unreinforced brick walls (Fig. 5.3). Roofs are mostly constructed from corrugated steel sheets. According to Reese et al. (2007), this type of structure is vulnerable to flood depths of greater than 2 m, and from observations of other types of extreme flood events, such as tsunamis, lahars, and debris flows, only the concrete floor is likely to remain intact after the passage of a ≥2 m flood (Reese et al. 2007). Hence, for each one of the three scenarios simulated for each lake, the impact on the downstream communities was estimated taking into account two inundation depths (1) the extent of the flood from the >0 m flood depth, and (2) the extent of the flood from the >2 m flood depth.

Fig. 5.3. Photos illustrating typical brick structures with roofs made from corrugated steel sheets. Pelechuco (A and B), Sorata (C). Photo credit: Dirk Hoffmann

5.3 Results

5.1.8 Modelling the 2009 Keara GLOF

The pre-GLOF lake area for Keara was 0.034 km^2, measured from an August 2005 satellite image in Google Earth. When multiplied with the lake depth (equation 1), the resulting lake volume is between 0.14×10^6 m^3 and 0.39×10^6 m^3, where the range in values accounts for potential errors in the relationship between depth, area and volume (see Section 2.2) (Table 5.1). Fig. 5.4 illustrates a simulation of the Keara event with the intermediate scenario (Table 5.1), as well as images taken shortly after the GLOF. Comparison of the incision and inundation displayed in the field photos with the flow depths and inundation extents of the numerical model shows good agreement. In location A, the flood depth was 4-6 mat the same location as the accompanying photo, which shows a ~5 m deep incision through proglacial till (Fig. 5.4). In location B, the model replicates flood inundation around farm buildings and walls with favourable comparison to the accompanying field photo. In zone C (Fig. 5.4 and Fig. 5.5), it is observed that infrastructure is only affected by flows that do not exceed 2 m, showing favourable comparison with the real event since no dwellings were destroyed during the GLOF.

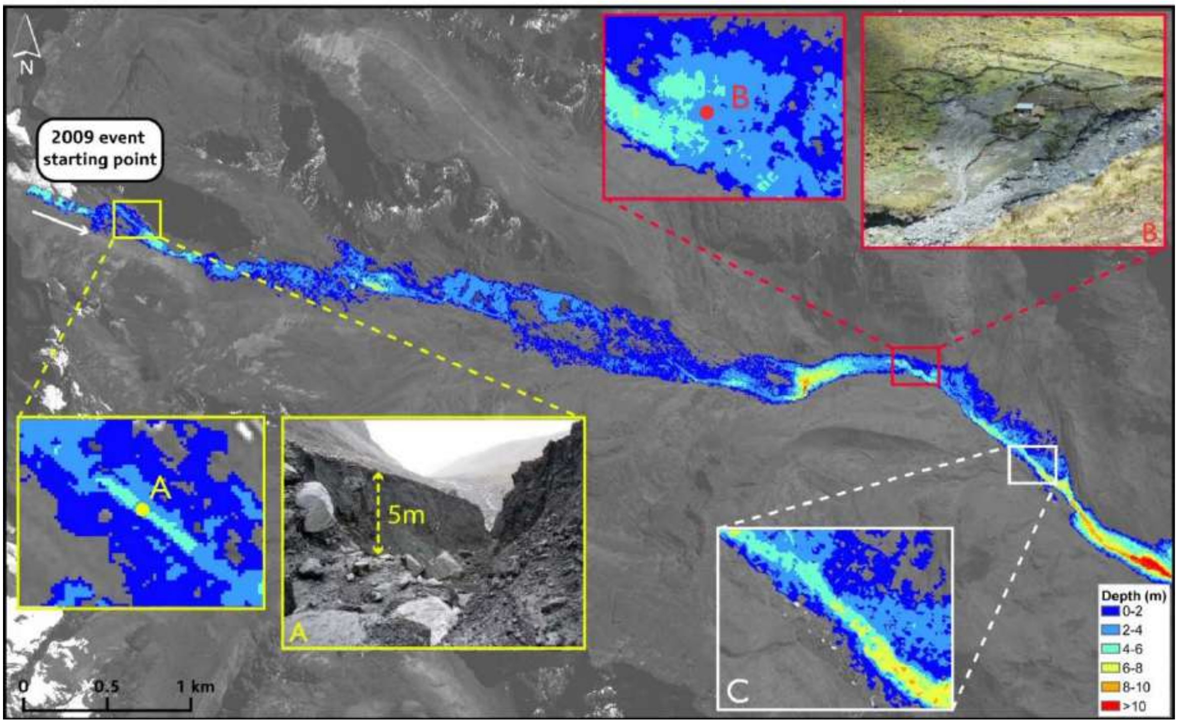


Fig. 5.4. Numerical simulation of the Keara November 2009 GLOF event. Zone A shows 4-6 m flow depths corresponding a ~5 m deep incision through proglacial till illustrated in the field photo. Zone B replicates flood inundation areal extent around farm buildings and walls with favourable comparison to the accompanying field photo (note that the photograph is taken from a different orientation to the model run image). Zone C illustrates impacts on the Keara community (a focused view is presented in

Fig. 5.5). The photos were taken in the field on November 3rd 2009, only hours after the event, by Martin Apaza Ticona, and used with his permission.

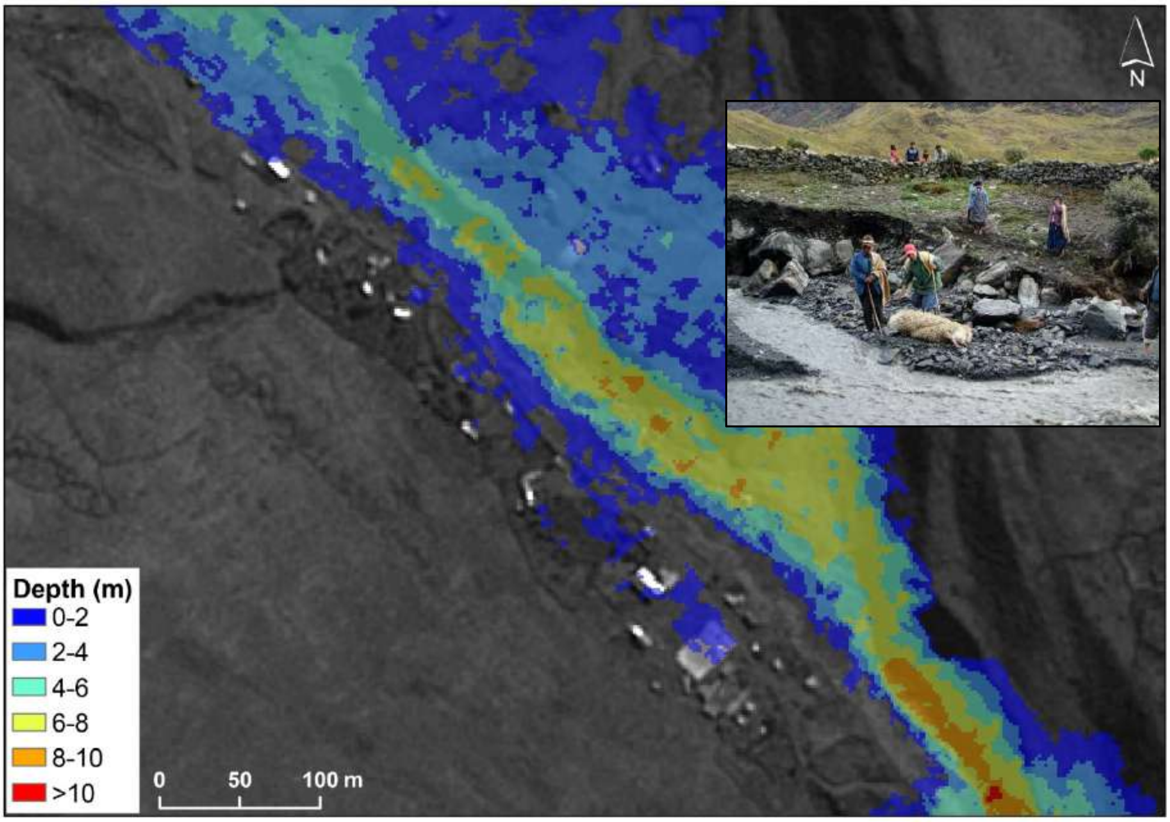


Fig. 5.5. Focused view of impacts on the Keara community. Photo credit: Martin Apaza Ticona.

5.1.9 Potential GLOF impacts from three dangerous lakes

5.1.9.1 Pelechuco lake

Two communities (Agua Blanca and Pelechuco) are situated downstream of Pelechuco Lake (Fig. 5.6). Agua Blanca is ~8.5 km from the lake, and has a total population of 379 individuals (Table 5.3). Agua Blanca is the only threatened community for which the ASTER GDEM is used in the hydraulic modelling because the SPOT-derived 2 m DEM contains a gap at this location due to terrain shading. Agua Blanca is also the smallest community (~30,600 m^2; Table 5.3), meaning that the 30 m ASTER GDEM offers a rather crude estimation of flood impact. Model results indicate that around 111 to 372 people could be affected by the flood, and between 69 to 335 of those people could be affected by potentially damaging flood waters of ≥2 m depth (Table 5.3). Damaging floods are considered here to be life threatening events or events causing significant damage to infrastructure. Fig. 5.6 provides a visualisation of the inundated areas downstream of Pelechuco lake.

The village of Pelechuco is about three times larger than Agua Blanca in terms of population number (981 individuals), and sits ~12.5 km from the lake. The three scenarios show that between 410 and 959 individuals could be affected by a GLOF, and that between 259 and 934 people could be affected by damaging (≥2 m depth) floods (Table Table 5.3).

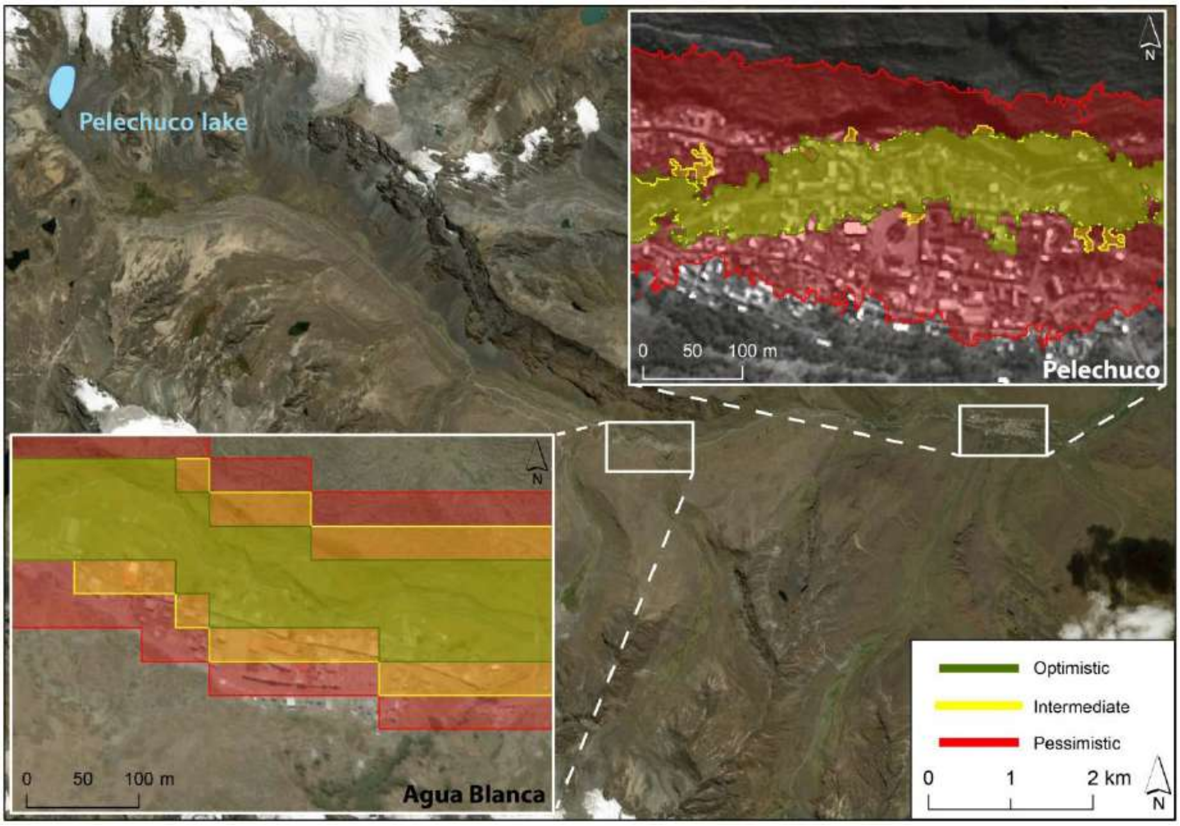


Fig. 5.6. Potential impacts for each modelled scenario for a GLOF (>2 m flood depth) originating from Pelechuco lake. ASTER GDEM (30 m resolution) was used for Agua Blanca, because gaps created by shading on the 2 m SPOT extracted DEM made evaluation impossible. For Pelechuco, the 2 m DEM was used.

Table 5.3. Potential GLOF impact scenarios for all six villages under threat.

Lake	Community	Cordinates (UTM)	Population[2]	Buildings[2]	Buildings affected[3]			Number of individuals per building	Population affected[3]		
					optimistic	intermediate	pessimistic		optimistic	intermediate	pessimistic
Pelechuco	Agua Blanca[1]	(19 L 488223 8361443)	379	164	48 (30)	53 (36)	161 (145)	2.31	111 (69)	122 (83)	372 (335)
	Pelechuco	(19 L 492374 8361658)	981	455	190 (120)	210 (135)	445 (433)	2.16	410 (259)	453 (291)	959 (934)
Laguna Glaciar	Sorata	(19 L 537548 8256109)	2788	1242	30 (8)	37 (10)	40 (40)	2.24	67 (18)	83 (22)	90 (90)
Laguna Arkhata	Totoral Pampa	(19 K 626722 8167167)	301	94	80 (70)	82 (75)	85 (80)	3.20	256 (224)	263 (240)	272 (256)
	Tres Rios	(19 K 628781 8167603)	303	173	150 (142)	170 (164)	173 (173)	1.75	263 (248)	298 (287)	303 (303)
	Khanuma	(19 K 631074 8167644)	223	81	12 (9)	15 (12)	75 (73)	2.75	33 (25)	41 (33)	206 (201)
All lakes	All communities		4975	2209	510 (379)	567 (432)	979 (944)		1140 (843)	1260 (956)	2202 (2119)

[1]For Aguablanca, due to gaps on the 2m DEM extraction ASTER 30m GDEM was used to estimate potential impacts.

[2]2015 dataset from GeoBolivia, which refers to the 2012 population census from the Bolivian National Statistical Institute.

[3]In parenthesis, >2m depth flood impacts on buildings and population

5.1.9.2 Laguna Glaciar

Laguna Glaciar is situated above the community of Sorata, which is home to ~2788 individuals and is also a popular hiking and climbing destination for tourists. The largest part of the community is situated between ~100 and 250 m above the meltwater channel and floodplain, and so is largely safe from any immediate GLOF impacts. However, a small part of the town sits close to the channel. Our modelling reveals that between 67 and 90 people could be affected by the flood, and between 18 and 90 of those people could be affected by floods of ≥2 m depth (Table 5.3; Fig. 5.7).

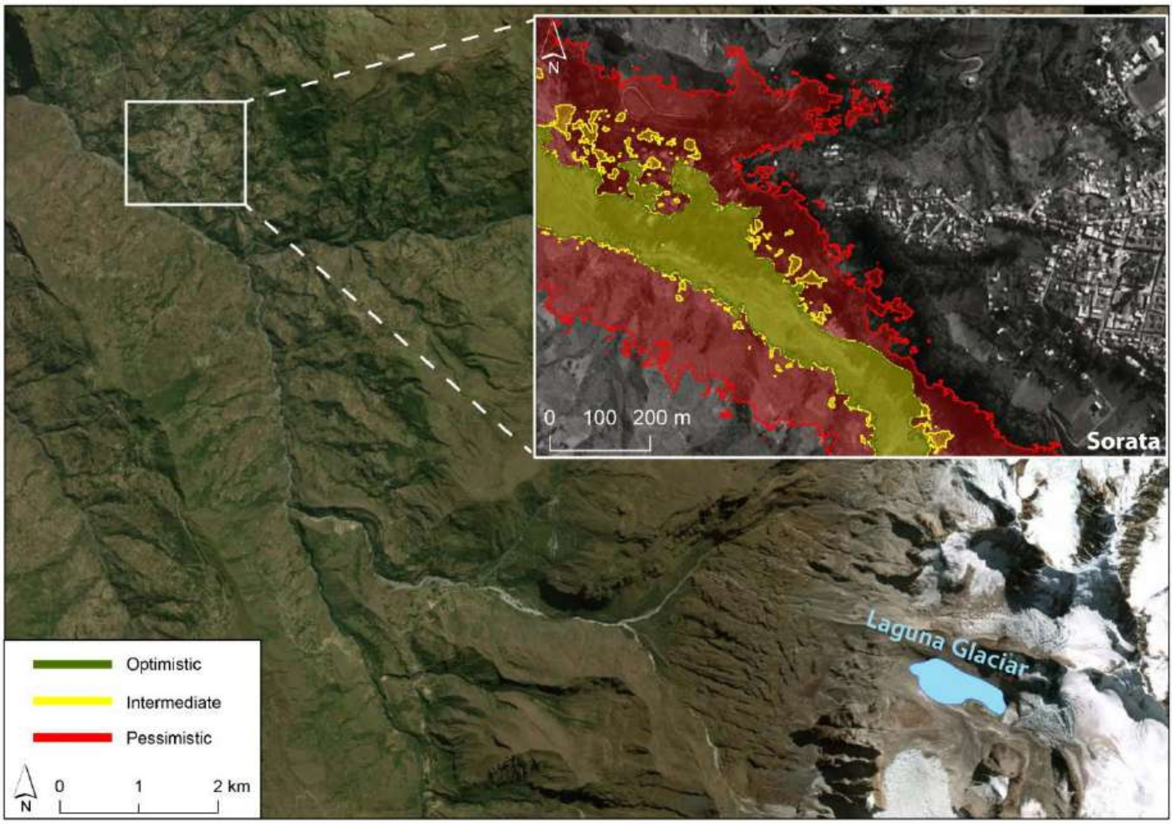


Fig. 5.7. Potential impacts for each modelled scenario for a GLOF (>2 m flood depth) originating from Laguna Glaciar.

5.1.9.3 Laguna Arkhata

Of all the glacial lakes in Bolivia, Kougkoulos et al. (2018) found that Laguna Arkhata represented the greatest risk to downstream communities. Totoral Pampa is the closest community to the lake (~6 km downstream), and is situated mostly within the floodplain of the meltwater stream that drains from the lake. Our modelling revealed that a GLOF could affect between 256 and 272 people (Table 5.3; Fig. 5.8). Therefore, even the optimistic scenario could affect most of the community.

Tres Rios, situated ~2 km downstream from Totoral Pampa, is located entirely on the floodplain. Thus, our modelling revealed that most of the community could be affected by a flood and 250 to 300 individuals could be exposed to potentially damaging floods.

Khanuma, which is situated another ~2 km downstream of Tres Rios, could be impacted to a lesser extent than the other two villages close to Laguna Arkhata. Modelling revealed that between 33 and 206 individuals could experience some flooding, and 25 to 201 of those people could be affected by damaging floods (Table 5.3; Fig. 5.8).

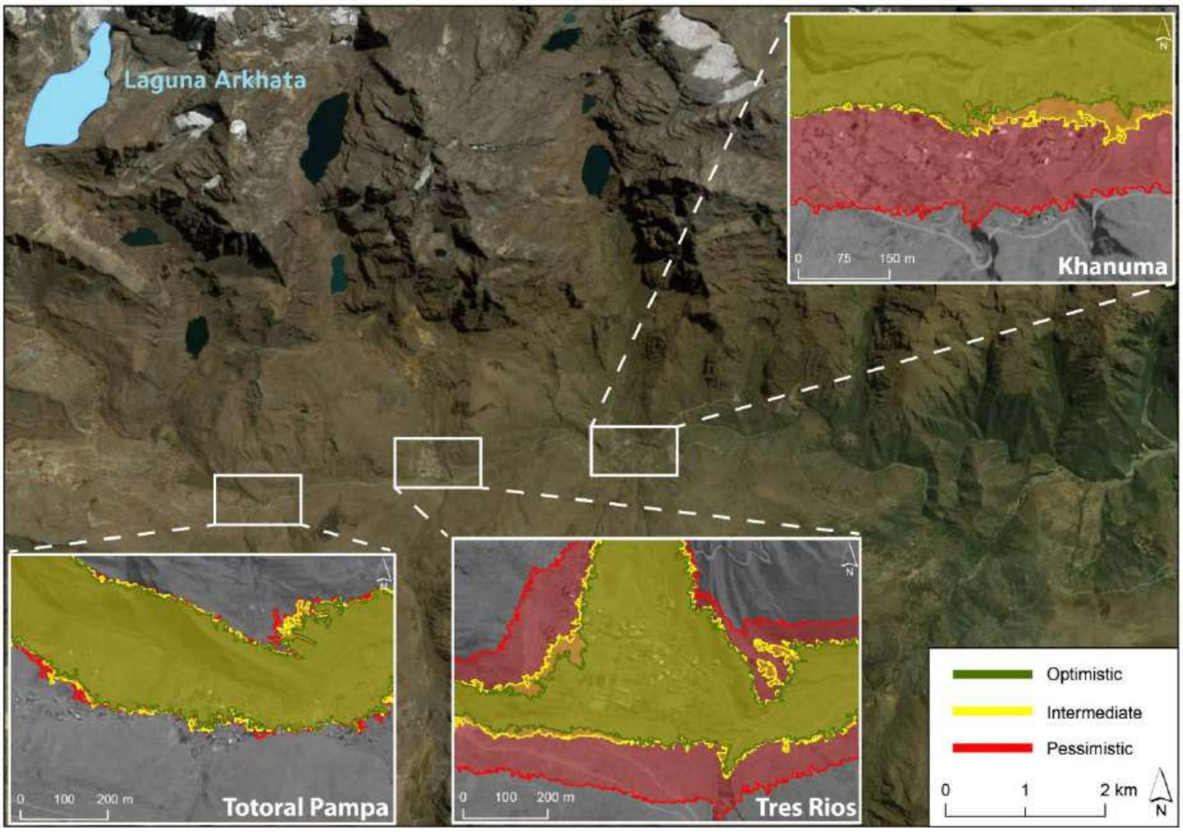


Fig. 5.8. Potential impacts for each modelled scenario for a GLOF (>2 m flood depth) originating from Laguna Arkhata.

5.4 Discussion

5.1.10 Modelling approach

For the first time, a hydrodynamic modelling study of GLOFs in the Bolivian Andes was undertaken. For the most part, this assessment was achieved using a 2 m resolution DEM derived from SPOT 6/7 imagery as data input, and HEC-RAS 5.0.3 to model clear-water flood flows. Our approach of producing and using a 2 m resolution DEM in favour of using coarser resolution, but freely available DEMs, such as ASTER GDEM or SRTM, offered us the best spatial resolution dataset available to drive our model without having to resort to field-based topographic data acquisition through differential-GPS (d-GPS), LiDAR, or Structure-from-Motion (SfM) surveys. Coarser resolution DEMs have been used routinely in GLOF modelling (e.g. Anacona et al. 2015; Wang et al. 2015a), but our approach offers arguably more robust results for relatively narrow streams and valleys that may, in some parts of the reach, be on a scale at or below the spatial resolution of coarser DEMs. Hence, our 2 m DEMs offer a good balance between spatial resolution and convenience of data access, while maximising the veracity of numerical modelling output and facilitating a more robust risk assessment of downstream GLOF impacts.

HEC-RAS 2D was employed to model GLOFs because it is available free-of-charge, works directly in ArcMap, which is convenient , and has been used successfully in previous studies to model GLOF inundation (e.g. Bajracharya et al., 2007; Dortch et al., 2011; Klimeš et al., 2014; Anacona et al., 2015; Wang et al., 2015; Watson et al., 2015). The 2D version of the model has a number of advantages over 1D models. Firstly, it offers the ability to simulate multi-directional and multi-channel flows (in contrast, 1D models are only capable of routing flow in one direction, i.e. downstream). Second, it models super-elevation of flow around channel bends, hydraulic jumps (i.e. in-channel transitions between supercritical and subcritical flow regimes), and turbulent eddying (Westoby et al. 2014a). These conditions are characteristic of GLOFs, so it is advantageous to be able to model them effectively. Furthermore, with a 2D model, assessing people and properties at risk becomes a simpler task as there is no need to interpolate 1D results across the floodplain.

An issue for consideration was that HEC-RAS was used to model clear-water flows when it is likely that sediment will be entrained into the flow, changing its rheology, and thereby affecting its travel distance and downstream impacts. Westoby et al. (2014a) indicate that debris flows (with sediment comprising at least ~20% of flow volume) are more common than clear-water flows in GLOFs from moraine-dammed lakes. Furthermore, debris-laden flows will travel shorter distances than clear-water flows (Huggel et al. 2004). Therefore, in some cases they may not reach as far as our modelled clear-water flows, but will induce more damage to population and infrastructure situated in close proximity to the pro-glacial lakes (Reese et al. 2007; Jakob et al. 2012). Nonetheless, our study is not unusual in modelling GLOFs as clear-water flows (e.g. Anacona et al. 2015; Kropáček et al. 2015; Wang et al. 2015b; Watson et al. 2015). HEC-RAS 2D offers the possibility to include sediment entrainment in the unsteady flow simulations, which may improve the representativeness of the modelled floods. This would require field data on the sedimentary nature of potential flood channels and dams, which would be worthwhile obtaining in future studies. Given these uncertainties, the robustness of our modelling approach was tested against field data following the ice-dammed lake outburst at Keara, in the Apolobamba region (Fig. 5.1 and Fig. 5.4). Comparison of our modelled flood inundation and flow depth results with documentary evidence of GLOF impacts illustrates that the model produced realistic results (Fig. 5.4 and Fig. 5.5).

A limitation of the HEC-RAS model is that, although it can model sediment entrainment, it cannot model debris flows that may result from a GLOF (Wang et al., 2015). Unfortunately, cost constraints and a lack of field data on channel and moraines sediments did not permit the use of models such as RAMMS, which have been used in previous studies to model GLOFs and debris flows originating from such events (e.g. Frey et al., 2016). Other options that have been used to model GLOFs include FLO-2D (e.g. Somos-Valenzuela et al., 2016), the PRO version of which comes at a cost, but which can be used to model debris flows; and BASEMENT (e.g. Worni et al., 2012; 2013; Lala et al., 2017), which is downloadable free-of-charge, but cannot model debris flows. A direct comparison of the outputs of each of these modelling tools is beyond the scope of this study, but it would be worthwhile undertaking such work in the future for the three lakes investigated here. Further, recent GLOF studies, have attempted to model complex process-chains in a multi-hazard proglacial lake context (e.g. Lala et al., 2017; Mergili et al., 2018), and it is suggested here that investigation of process chains for GLOFs from proglacial lakes in Bolivia would be a valuable undertaking in the future.

Some uncertainties in our modelling include the volume of the lakes, the appropriate Manning’s value to use for the channel, and the population living within each community. Hence, a field study of lake bathymetries, the nature of stream sediments, and a survey of the number of community occupants, which may change seasonally, would be welcome.

5.1.11 GLOF impacts and risk management

Kougkoulos et al. (2018) identified three glacial lakes across Bolivia that represent medium and high GLOF risk. Table 5.3 provides a summary of the potential impacts of GLOFs from those three lakes, and Figs. 6, 7 and 8 give a visualisation of flood inundation for each affected community. In total, there are six communities at risk, which are home to ~4975 people and 2209 buildings. Our modelling results indicate that between 1140 and 2202 people could be affected by GLOF events if all three lakes burst and between 843 and 2119 of those people could be impacted by potentially damaging floods where the flow depth is modelled to be ≥2 m. Fig. 5.9 provides a summary and comparison of GLOF impacts across the study sites.

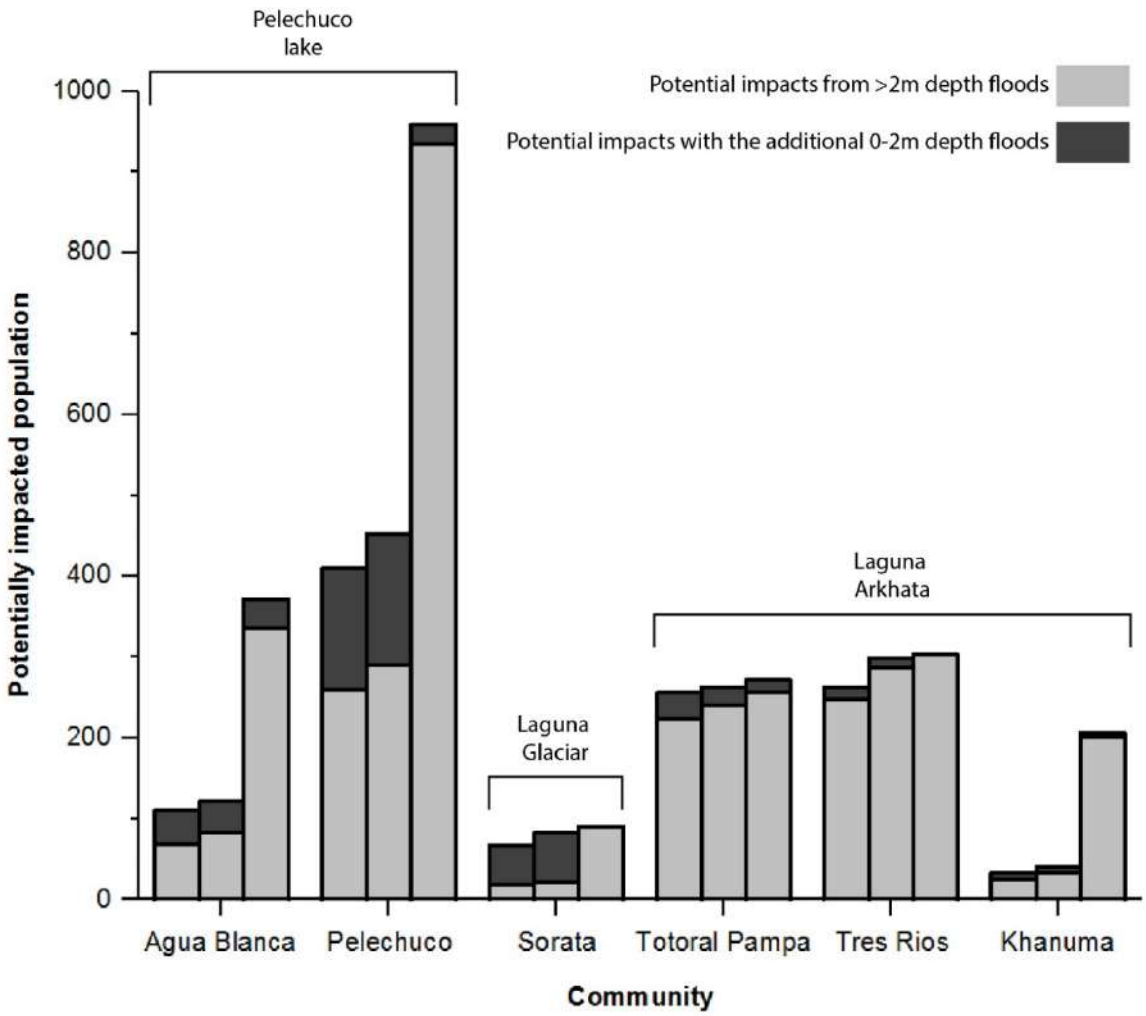


Fig. 5.9. Potentially affected population numbers per community and per modelled scenario. Left (optimistic), Centre (intermediate), Right (pessimistic).

5.1.11.1 Pelechuco Lake

Our results indicate that Pelechuco lake should be a priority for risk mitigation efforts. Kougkoulos et al. (2018) ranked this lake as 'medium' risk, and the modelling results presented in the current study show that part of both downstream communities (Agua Blanca and Pelechuco) could be severely damaged by potential flooding. Pelechuco in particular stands out on Fig. 5.9 as having the greatest number of potentially impacted people across all three lakes investigated. This is despite the fact that Pelechuco lake is the smallest of the three lakes examined here, and hence generates the smallest floods (Table 5.3). The high number of potentially impacted people results from the high proportion of the village area that is situated along the riverbanks (Fig. 5.6). The impact of a flood from Pelechuco lake on the community of Agua Blanca may require further detailed field investigation because only the 30 m resolution ASTER GDEM was available to drive the HEC-RAS model at this section of the channel reach (Fig. 5.6).

5.1.11.2 Laguna Glaciar

Of the three lakes, Laguna Glaciar arguably represents the lowest priority for risk managers in Bolivia. Kougkoulos et al. (2018) ranked the lake as medium risk, and our results indicate that, because a large part of the community of Sorata is situated far from the floodplain, the impacts of a GLOF would be relatively low (Fig. 5.7 & Fig. 5.9). Cost-benefit analysis between relocation of the part of the community potentially hit by a flood and a combination of sustaining GLOF awareness programmes and early warning systems could be worthwhile undertaking for local risk managers and stakeholders. Ongoing monitoring of the lake and its surroundings as the glacier continues to recede would certainly be valuable.

5.1.11.3 Laguna Arkhata

Laguna Arkhata is a bedrock-dammed lake, and hence the probability of the dam failing and the lake draining completely is low; the most likely scenario would be an ice, snow or rock avalanche impacting the lake and generating a wave that overtops the bedrock dam. However, irrespective of the drainage scenario (optimistic to pessimistic), the numbers of people affected by GLOFs varies relatively little for Totorampa and Tres Rios; the differences are more marked for Khanuma. All three communities are affected by floods because they are located on floodplains. The communities of Totoral Pampa and Tres Rios look particularly vulnerable to GLOFs Totoral Pampa would be the first to be hit by a GLOF, and no matter what scenario is used in the modelling (from pessimistic to optimistic), Tres Rios is almost completely inundated from all flood scenarios because of its position on a floodplain (Fig. 5.8 &

Fig. 5.9). This provokes the question of whether any structural or non-structural measures could be applied in these communities (e.g. GLOF awareness programmes, flood defence construction, community relocation, etc.). Future studies could focus on analysing the benefit of a manged retreat, by basically relocating most of the community outside the risky areas which is an increasingly discussed technique in the context of climate change for numerous regions facing various types of natural hazards around the world (Hino et al., 2017).

5.5 Conclusion

For the first time, potential glacial lake outburst floods (GLOFs) in the Bolivian Andes were modelled. This was achieved using high-resolution (2 m per pixel) DEMs derived from (tri-) stereo SPOT satellite imagery to drive a 2D hydrodynamic model (HEC-RAS 5.0.3). The modelling approach was first tested against field evidence from a documented GLOF event at Keara in the Apolobamba region in 2009, and was shown to reproduce realistic flood depths and inundations. The model was then applied to three lakes that have been identified previously as representing a GLOF risk to downstream communities (Kougkoulos et al. 2018). These are Pelechuco lake, in the Apolobamba region, and Laguna Glaciar and Laguna Arkhata, in the Cordillera Real. GLOFs from all three lakes were shown to represent potentially life-threatening and/or damaging events. In total, GLOFs from the three lakes would impact six downstream communities. As a sensitivity analysis, our model was run for three scenarios, representing pessimistic, intermediate and optimistic scenarios, by varying model parameterisation. These scenarios give a range in the number of impacted people. In total, between 1140 and 2202 people would be affected by flooding if all lakes were to burst; and between 843 and 2119 of those people would be exposed to damaging floods (flow depth ≥2 m). Laguna Arkhata and Pelechuco lake represent the greatest GLOF risk due to the large numbers of people who live in the potential flow paths, and hence should be a priority for risk managers.

Chapter 6

Conclusions and further research

6.1 Conclusions

The main aims of this PhD were: (1) to evaluate recent glacier area change and proglacial lake development (1986 - 2018) in the Bolivian Cordillera Oriental; (2) to identify glacier bed overdeepenings that could host proglacial lakes in the future across the same area; and (3) to assess the risk posed by glacial lake outburst floods (GLOFs) across the same area.

Four objectives were devised in order to meet the research aims, as presented in section 1.4. The main conclusions reached for each objective are as follows:

Objective 1 - Quantification of glacier area changes and proglacial lake development from 1986 to 2018 across the Bolivian Cordillera Oriental as well as range and altitude division results:

- This study expands on the results presented by Cook et al. (2016), illustrating that glaciated areas have decreased from 529 km^2 to 281 km^2 (49%) in the Bolivian Cordillera Oriental from 1986 to 2018. The number of proglacial lakes and their areas (i.e. those that formed within 500m of the 1986 ice margin) increased as glaciers have receded from their 1986 positions. The number of proglacial lakes increased from 145 to 229; an increase of 58%. This general increase in the number and size of proglacial lakes across the study period, in accordance with several studies of proglacial lake development elsewhere in the world, indicates that ongoing monitoring of these lakes is required since they have the potential to generate GLOFs that could be damaging to downstream communities. Risk assessment of these lakes and hydrological modelling of GLOFs has been tackled in objectives 2, 3 and 4.

- This is also the first study illustrating differences in the rate of glacier mass loss between the east-facing and west-facing sides of the Cordillera Oriental. The east-facing side has experienced faster glacier shrinkage, with glaciated area decreasing from 258 km^2 to 128 km^2 (50 %) while the west-facing side has shrunk from 271 km^2 to 153 km^2 (44 %). In terms of the altitudinal controls, glaciers situated below 5000 m asl. in the Bolivian Cordillera Oriental have already become nearly extinct with only small ice patches remaining, representing an area of 7 km^2. Glaciers situated from 5000 to 5500 m asl. have shrunk from 376 km^2 to 199 km^2 (47 %). Glaciers situated over 5500 m asl. declined in area from 100 km^2 to 73 km^2 (23 %). These glaciers represent an important regional water source, and hence there is significant concern with respect to the sustainability of that water supply in a changing climate.

Objective 2 - Identification of subglacial overdeepenings beneath glaciers (as extracted from 2018 data) and first-pass risk assessment of potential future lakes:

- Sixty-eight glacier-bed overdeepenings have been identified across the entire Bolivian Cordillera Oriental, which may host proglacial lakes in the future, as glaciers continue to recede. The future lake areas vary from ~0.01 km^2 to ~0.5 km^2 and their total water volume could reach ~80,000,000 m^3. These future lakes could pose a GLOF risk for downstream communities, but they may also represent water storage facilities. This is the first study globally to assess the risk from lakes that have not yet emerged from under the ice. The assessment was achieved using open-source and no-cost data and software. In detail, Google Earth and the GlabTop method (Linsbauer et al., 2012) have been used to identify locations of potential future lakes and potentially impacted population numbers.

- Moreover, a simple geometric model (MC-LCP; Watson et al., 2015) was used to estimate downstream GLOF inundation. Modelling of impacts on the 12 downstream communities, with two sensitivity scenarios (optimistic and pessimistic) has shown that between ~1100 and ~2900 people could be affected by flooding if all lakes were to appear and to burst. After the evaluation of the hazard parameters for the 8 future lakes and the impacts on downstream communities, the risk assessment demonstrated that future lake A (upstream from the community of Puina) represents the highest risk (medium) for both optimistic and pessimistic scenarios, and therefore its potential future appearance requires ongoing monitoring. In addition, lakes C, F and G turn from low (optimistic) to medium (pessimistic) risk and their potential appearance should be monitored in the future. Potential lakes B, D, E, H do not seem to present significant risk under current conditions but that situation could change, and should be assessed over time.

Objective 3 - Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes:

- This is the first study that makes use of multi-criteria decision analysis to assess the risk from potentially dangerous glacial lakes. Its key characteristics are that: a) it makes use of freely and widely available data inputs and software without requiring a field study; b) it can be applied across a range of glacial lake contexts (ice-dammed, moraine-dammed, etc.) simultaneously, and to any region of the world; c) it enables researchers to make a first-pass analysis of potentially dangerous lakes objectively before committing to further investigation (e.g. field work, remote sensing data analysis); and d) it readily permits sensitivity testing of the model. Crucially, the first stage of the MCDA approach (the Description Problem) involves the determination of appropriate criteria by which to define risk.

- Sixteen potentially dangerous glacial lakes were assessed as well as six lakes that have already generated GLOFs in the past (between 2004 and 2013). The results for the 16 extant lakes compare favourably with previous risk and hazard assessments, which have generally focused on specific regions or glacial lake contexts. This indicates that the MCDA model can be applied in a range of contexts globally. Further, sensitivity analyses of the model were undertaken to explore the robustness of results and model assumptions. This was the first sensitivity analysis of a GLOF risk assessment model ever undertaken.

- The method was then applied to 25 glacial lakes in the Bolivian Andes (as identified as representing a potential GLOF risk by Cook et al., 2016), and illustrates that 22 of these lakes represent low risk, and therefore do not currently require immediate further attention. Nevertheless, further detailed investigation or action is required for two lakes rated as medium risk (Pelechuco, Laguna Glaciar), and one lake rated as high risk (Laguna Arkhata).

Objective 4 - Modelling glacial lake outburst flood impacts in the Bolivian Cordillera Oriental:

- Here, the three lakes identified as medium- and high-risk from objective 3 were subjected to further analysis. 2D hydrodynamic modelling (HEC-RAS 5.0.3) was undertaken on high-resolution (2 m per pixel) DEMs derived from (tri-) stereo SPOT satellite imagery.

- The hydrodynamic modelling approach was first tested against field evidence from a documented GLOF event at Keara in the Apolobamba region in 2009, and was shown to reproduce realistic flood depths and inundations. It was then applied to the three potentially dangerous lakes (Lake Pelechuco, Laguna Glaciar, Laguna Arkhata) and it was concluded that six downstream communities could be impacted if all three lakes generated GLOFs.

- By way of a sensitivity test, three model scenarios were run for each lake, representing pessimistic, intermediate, and optimistic scenarios. This was achieved by varying model parameterisation (i.e. outburst duration, Manning's value, drainage volume). These scenarios give a range in the number of impacted people. In total, between 1140 and 2202 people could be affected by flooding if all lakes were to burst, and between 843 and 2119 of those people could be exposed to damaging floods (flow depth ≥ 2 m). Laguna Arkhata and Pelechuco lake represent the greatest GLOF risk due to the large numbers of people who live in the potential flow paths, and hence should be a priority for risk managers.

6.2 Future research

This study has reached key conclusions around the stated research aim. However, in undertaking this research, it has become apparent that much remains to be done in the field of glacier change and associated risks in the Bolivian Andes. Further, related research avenues were brought to light during a workshop organised through this thesis work, which took place in La Paz in July 2018 (Appendix 6.1). Overall, it is suggested that the following themes require further research attention:

6.2.1 Glacier demise and water scarcity

Chapter 3 has shown that the Bolivian Cordillera Oriental has experienced sustained and widespread glacier area reduction in recent decades. Improved modelling of upcoming glacier changes in Bolivia could provide accurate estimates of remaining water resources in the area. For instance, Drenkhan et al. (2018) applied a low-emission (RCP2.6) and a high-emission (RCP8.5) IPCC scenario to observe potential glacier extent in the neighbouring Vilcanota-Urubamba basin of the Peruvian Andes. They found that future glacier areas could decrease substantially by a further ~41% (RCP2.6) to ~45% (RCP8.5) until 2050, and by ~41% (RCP2.6) to ~93% (RCP8.5) by 2100. Yarleque et al. (2018) analysed the future state of Quelccaya Ice Cap (QIC), found that from the mid-2050s onwards, the ELA will be located above the QIC summit and increasingly negative mass balances will persist for most tropical glaciers of similar elevations like the Bolivian Cordillera Oriental. Future studies on Bolivian glacier change should focus on similar scenarios in an attempt to estimate glacier losses until the end of the 21st century. Moreover, reliable quantification of runoff changes is crucial for water allocation. Soruco et al. (2015) have provided runoff estimations using a water balance model for four major watersheds upstream from the city of La Paz and they found 15 % contribution from glacial meltwater to water resources at an annual timescale. Nevertheless, as Guido et al. (2016) underline, meteorological and discharge data are often lacking in remote areas and in developing nations, that is why they used environmental tracers to estimate runoffs in the Condoriri watershed, again in the Cordillera Real. The same approach could be used in the remaining two Cordilleras (Apolobamba and Tres Cruces) since no studies have focused in these regions before and meteorological data are far from abundant. Other social-economic and cultural issues occurring from shrinking glaciers and which merit to be studied in detail are related to (1) hydropower generation in La Paz and El Alto which depends to some extent on glaciers (Liniger et al. 1998; Painter, 2007), (2) the disappearance of glaciers attracting tourism, such as the Chacaltaya in Cordillera Real, which used to be the site of the highest ski lift in the world (Chevallier et al. 2011) as well as (3) cultural belief systems, spiritual values and perceptions since they form an integral part of water management practices in Bolivia and the tropical Andes in general (Vuille et al., 2018).

6.2.2 Ice thickness and climatic data monitoring

Long-term monitoring of glaciers of the Bolivian Cordillera Oriental is essential. On-site measurements such as GPR studies, which only exist today for the Zongo glacier (e.g. (Francou et al., 1995; Rabatel et al., 2013; Réveillet et al., 2015) are required for different Bolivian glaciers in order to offer validation of estimations from ice-thickness modelling approaches (Linsbauer et al., 2012). As an example, in Chapter 3 of this study, the ice thickness estimates of the Zongo glacier derived from the GlabTop method are in accordance with the GPR data provided by Réveillet et al. (2015). Therefore, the volumes extracted in this study with the GlabTop method gave around 9.0×10^7 m^3 in 1999, whereas Réveillet et al. (2015) found around 9.7×10^7 m^3 in 1997. The favourable comparison between field and GlabTop modelling results is encouraging, but more needs to be done to ground-truth model results at other glaciers. Concerning climate records, even though the Servicio Nacional de Meteorologia e Hidrologia (SENAMHI) provides important data (e.g. temperature, precipitation) from a large number of meteorological stations around Bolivia, the lack of stations located in high-altitudes (>5000 m asl.) limits the reliability of glacier change projections. More importantly, numerous studies (e.g. Sorruco et al., 2015; Veettil et al., 2018) underline the need for these measurements in order to establish accurate projections for critical periods of water scarcity in Bolivian semi-arid regions.

6.2.3 Proglacial lake development and GLOF hazard and risk assessments

All three result Chapters of this thesis (3, 4, 5) were dedicated to the study of GLOFs in Bolivia. Nevertheless, there are still issues that can be addressed in future studies. Firstly, population estimates were provided for each potentially impacted community through GeoBolivia (2012 population census). However, it is difficult to know the precise number of people that would be affected by flooding if the most dangerous glacial lakes were to burst. Specifically, without detailed field studies it is impossible to know the exact numbers of occupants per house in each community since there are likely to be spatial differences as well as temporal variations due to seasonal migration within Bolivia (Oxfam, 2009). In addition, field studies serve to inform a number of vulnerability parameters (discussed in detail in Chapter 4 - Kougkoulos et al., 2018a), which cannot be determined remotely. Secondly, the SPOT 6/7 imagery used in this study is a major improvement compared to other past studies which use coarser open-source DEMs (30 m or 90 m). However, the highest risk glacial lakes (e.g. Laguna Arkhata, Laguna Glaciar, Pelechuco lake) could also profit from extended field studies using Unmanned Aerial Vehicles (UAVs) or laser scanning to survey (in more detail) the lake environment and areas downstream (e.g. Lala et al. 2017; Mergili et al. 2018). During the field studies, other factors connected to hydraulic properties addressed in previous Chapters (4 and 5) could also be evaluated for the lakes in consideration. These factors include the correct evaluation of the Manning's roughness value (Marcus et al., 1992), as well as dam stability, which is hard to evaluate remotely (Chapters 4 and 5 - Kougkoulos 2018a, 2018b). Moreover, research focusing on past events could be of interest in order to better inform the numerous parameters operating during a GLOF event like the outburst duration or the drainage percentage (see Chapter 5 - Kougkoulos et al., 2018b). This has been done for other mountain ranges around the world (e.g. Vilímek et al., 2015; Emmer, 2017 - in the Peruvian Andes; Westoby et al., 2014b; Miles et al., 2018 - in the Nepalese Himalaya). In the Bolivian Cordillera Oriental, the only documented GLOF took place in Keara in 2009 and provoked major damage to the downstream community as well as changes to the ecosystem and channel geomorphology (Hoffmann and Wegenmann, 2013; Kougkoulos et al., 2018a, 2018b). Lastly, except being a potential threat to downstream communities, glacial lakes can provide valuable water resources. Past studies from Vuille et al. (2018) and Haeberli et al. (2016) underline the importance of water from glacial lakes for use by local population and energy production. Nevertheless they also indicate that the legal, social, cultural and political constraints for implementation remain considerable (Vuille et al., 2018). Huggel et al. (2016, 2018) have initiated the debate for a legal framework concerning the mountain cryosphere which could encompass risks an opportunities occurring from systems like glacial lakes.

6.2.4 Paraglacial processes

Church and Ryder (1972) define the term *paraglacial* as 'nonglacial processes that are directly conditioned by glaciation', which is characteristic of today's deglaciating environments. These environments are characterised by high rates of sediment delivery from slopes and into fluvial and aeolian systems (Benn and Evans, 2010). These processes occur once the support from glacier ice on steep rockslopes is removed uncovering unconsolidated glacial sediments (Benn and Evans, 2010). Haeberli et al. (2017) mention that due to the different response of glaciers, water, vegetation, rock slopes or permafrost, paraglacial landscapes will be characterized by strong disequilibrium, especially with respect to ecosystem evolution, erosion/sedimentation and slope stability which will lead to increasing risk from landslides and debris flows for population living downstream of these areas. It has been reported that the most active period of paraglacial sedimentation occurs with decades of deglaciation, and that the transition to lower sediment yields occurs with one or two centuries (Benn and Evans, 2010). In addition, rock slopes situated above shrinking glaciers are frequently subject to increased slope activity because of paraglacial processes (Ballantyne, 2002; Curry and Morris, 2004; Vehling et al., 2017). Due to recent glacier shrinkage in the Bolivian Andes, described in Chapter 3, paraglacial processes have to be carefully examined in order to inform river catchment management in light of changing sediment inputs, which could cause changes to the Bolivian high mountain ecosystem and human activities such as hydropower and tourism. Furthermore, these recently uncovered steep slopes could be more susceptible to landslides, which is a hazard in itself, but these in turn could trigger more GLOFs.

6.2.5 Debris-covered glaciers and rock glaciers

Debris-covered and rock glaciers differ mainly because of their ice-content (Barcaza et al., 2017). Janke et al. (2015) provided a classification scheme for debris-covered and rock glaciers in the Chilean Andes based on field observations and measurement of ice content. He suggests that both categories (Debris, Rock) are divided into three subclasses each. Concerning debris-covered glaciers, the first class (semi-covered) is situated under a thin layer of less than 0.5 m of debris and its ice content is around 85 %. The second class (fully covered) situated between 0.5 and 3 m of debris has 65 - 85 % ice and the third class (buried) which is located under >3 m of debris contains 45 - 65 % ice. As for rock glaciers, Janke et al. (2015) suggest that their internal ice is gradual reduced and the accumulation of surface debris as englacial material is exposed through downwasting of internal ice. The first class is situated entirely under debris and they typically contain 25 - 45 % of ice. The second class, contains 10 - 25 % of ice, which is segregated and therefore its flow decreases. Finally, the third class, which is mainly constituted by moraine debris contains less than 10 % of ice content (Janke et al., 2015).

The ice in rock glaciers is protected from small changes in temperature by an insulating layer of debris, making them more resilient to climate change than clean ice glaciers (Haeberli et al., 2006; Rangecroft et al., 2013, 2014, 2016). Rangecroft et al. (2014) focused on three Bolivian Cordilleras: Cordillera Real, Sajama and the Western Cordillera. They identified 94 rock glaciers, covering around 11 km^2. In addition about 87% of these glaciers were south-facing, suggesting the importance of reduced solar input for their development. Nevertheless, rock glaciers in the rest of the Cordillera Oriental (Cordillera Apolobamba and Cordillera Tres Cruces) were not investigated yet and therefore further studies could focus on these mountain ranges in order to anticipate additional water resources in the context of shrinking glaciers.

Concerning debris-covered glaciers, especially for the fully covered and the buried types (described in this section), the internal ice is preserved by an insulating cover of thick debris, which acts as a storage reservoir to release water during the summer and early fall (Janke et al., 2015). Therefore since these glaciers can also provide valuable water resources for Bolivian communities and an inventory of debris-covered glaciers in the Bolivian Cordillera Oriental could be of high value for local stakeholders and future planning in large cities (like La Paz and El Alto) in the face of ongoing glacier shrinkage.

References

Ageta Y, Iwata S, Yabuki H, Naito N, Sakai A, Narama C, and Karma (2000) 'Expansion of glacier lakes in recent decades in the Bhutan Himalayas.' In: Nakawo, M, Raymond CF, and Fountain A (eds) Debris-covered glaciers, Proceedings of a workshop held at Seattle, Washington, U.S.A., September, Wallingford: IAHS Publication 264: 165-175.

Aggarwal, A., Jain, S. K., Lohani, A. K. and Jain, N. (2013) 'Glacial lake outburst flood risk assessment using combined approaches of remote sensing, GIS and dam break modelling.' *Geomatics, Natural Hazards and Risk*, 7(1) pp. 18–36.

Aggarwal, S., Rai, S. C., Thakur, P. K. and Emmer, A. (2017) 'Geomorphology Inventory and recently increasing GLOF susceptibility of glacial lakes in Sikkim, Eastern Himalaya.' *Geomorphology*, 295 pp. 39–54.

Akgun, A. and Türk, N. (2010) 'Landslide susceptibility mapping for Ayvalik (Western Turkey) and its vicinity by multicriteria decision analysis.' *Environmental Earth Sciences*, 61(3) pp. 595–611.

Albert, T. H. (2002) 'Evaluation of Remote Sensing Techniques for Ice-Area Classification Applied to the Tropical Quelccaya Ice Cap, Peru.' *Polar Geography*, 26(3) pp. 210–226.

Alean, J. (1985) 'Ice avalanches: some empirical information about their formation and reach.' *Journal of Glaciology,* 31(109), 324–33.

Allen, S. K., Linsbauer, A., Randhawa, S. S., Huggel, C., Rana, P. and Kumari, A. (2016) 'Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats.' *Natural Hazards*, pp. 1–23.

Allen, S. K., Rastner, P., Arora, M., Huggel, C. and Stoffel, M. (2015) 'Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition.' *Landslides*, 13(6) pp. 1479–1491.

Allen, S. K., Schneider, D. and Owens, I. F. (2009) 'First approaches towards modelling glacial hazards in the Mount Cook region of New Zealand's Southern Alps.' *Natural Hazards and Earth System Science*, 9(2) pp. 481–499.

Anacona, P. I., Mackintosh, A. and Norton, K. (2015) 'Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia: Lessons for GLOF risk management.' *The Science of the total environment*, 527-528 pp. 1–11.

Anacona, P., Norton, K. P. and Mackintosh, A. (2014) 'Moraine-dammed lake failures in Patagonia and assessment of outburst susceptibility in the Baker Basin.' *Natural Hazards and Earth System Sciences*, 14(12) pp. 3243–3259.

Ashraf, A., Naz, R. and Roohi, R. (2012) 'Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis.' *Geomatics, Natural Hazards and Risk*, 3(2) pp. 113–132.

Bajracharya, B., Shrestha, A. B. and Rajbhandari, L. (2007) 'Glacial Lake Outburst Floods in the Sagarmatha Region.' *Mountain Research and Development*, 27(4) pp. 336–344.

Bakke, J. and Nesje, A. (2011) 'Equilibrium-Line Altitude (ELA).' *In* Singh, V. P., Singh, P., and Haritashya, U. K. (eds) *Encyclopedia of Snow, Ice and Glaciers*, pp. 268–277.

Ballantyne, C.K. (2002) 'A general model of paraglacial landscape response.' *The Holocene*, 12 pp. 371–376.

Barcaza, G., Nussbaumer, S. U., Tapia, G., Valdés, J., García, J., Videla, Y., Albornoz, A. and Arias, V. (2017) 'Glacier inventory and recent glacier variations in the Andes of Chile, South America.' *Annals of Glaciology*, 58 pp. 166–180.

Barry, R. G. (2006) 'The status of research on glaciers and global glacier recession: a review.' *Progress in Physical Geography*, 30(3) pp. 285–306.

Behzadian, M., Kazemzadeh, R. B., Albadvi, A. and Aghdasi, M. (2010) 'PROMETHEE: A comprehensive literature review on methodologies and applications.' *European Journal of Operational Research*, 200(1) pp. 198–215.

Benn, D. I. and Evans, D. J. A. (2010) 'Glaciers and Glaciation', Second edition, Hodder Education, London, 802 pp.

Benn, D. I., Owen, L. A., Osmaston, H. A., Seltzer, G. O., Porter, S. C. and Mark, B. (2005) 'Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers.' *Quaternary International*, 138–139 pp. 8–21.

Benn, D. I., Wiseman, S. and Hands, K. A. (2001) 'Growth and drainage of supraglacial lakes on debrismantled Ngozumpa Glacier, Khumbu Himal, Nepal.' *Journal of Glaciology*, 47(159) pp. 626–638.

Bennett, M. R. and Glasser, N. F. (2009) *Glacial Geology: Ice Sheets and Landforms*. Wiley.

Bolch, T., Buchroithner, M. F., Peters, J., Baessler, M. and Bajracharya, S. (2008) 'Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery.' *Natural Hazards and Earth System Sciences*, 8 pp. 1329–1340.

Bolch, T., Peters, J., Yegorov, A., Pradhan, B., Buchroithner, M. and Blagoveshchensky, V. (2011) 'Identification of potentially dangerous glacial lakes in the northern tian shan.' *Natural Hazards*, 59 pp. 1691–1714.

Bradley, R. S., Vuille, M., Diaz, H. F. and Vergara, W. (2006) 'Threats to Water Supplies in the Tropical Andes.' *Science*, 312 pp. 1755–1756.

Breien, H., De Blasio, F. V., Elverhøi, A. and Høeg, K. (2008) 'Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway.' *Landslides*, 5(3) pp. 271–280.

Brito, A. J., de Almeida, A. T. and Mota, C. M. M. (2010) 'A multicriteria model for risk sorting of natural gas pipelines based on ELECTRE TRI integrating Utility Theory.' *European Journal of Operational Research*, 200(3) pp. 812–821.

Brunner, G.W. (2010) 'HEC-RAS River Analysis System User's Manual. US Army Corps of Engineers, California.'

Budhathoki, K.P., Bajracharya, O.R. and Pokharel, B.K. (2010) 'Assessment of Imja glacier Lake outburst Flood (GLOF) Risk in Dudh Kosi River Basin using Remote Sensing Techniques.' *Journal of Hydrology and Meteorology*, SOHAM-Nepal, 7 (1).

Burns, P. and Nolin, A. (2014) 'Using atmospherically-corrected Landsat imagery to measure glacier area change in the Cordillera Blanca, Peru from 1987 to 2010.' *Remote Sensing of Environment*, 140 pp. 165–178.

Bury, J. T., Mark, B. G., Mckenzie, J. M., French, A., Baraer, M., In, K., Marco, H. and Zapata, A. (2011) 'Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca , Peru.' *Climatic Change*, 105 pp. 179–206.

Buxton, N., Escobar, M., Purkey, D., Lima, N. (2013) 'Water scarcity, climate change and Bolivia: Planning for climate uncertainties.' *Stockholm Environment Institute, Discussion Paper,* 4pp.

Buytaert, W., Moulds, S., Acosta, L., Bièvre, B. De, Olmos, C., Villacis, M., Tovar, C. and Verbist, K. M. J. (2017) 'Glacial melt content of water use in the tropical Andes.' *Environmental Research Letters*, 12 pp. 1–8.

Byers, A. C., Rounce, D. R., Shugar, D. H., Lala, J. M., Byers, E. A. and Regmi, D. (2018) 'A rockfall-induced glacial lake outburst flood, Upper Barun Valley, Nepal.' *Landslides*.

Carey, M. (2005) 'Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru.' *Global and Planetary Change*, 47 pp. 122–134.

Carey, M., Baraer, M., Mark, B. G., French, A., Bury, J., Young, K. R. and McKenzie, J. M. (2014) 'Toward hydro-social modeling: Merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru).' *Journal of Hydrology*, 518 pp. 60–70.

Carey, M., Huggel, C., Bury, J., Portocarrero, C. and Haeberli, W. (2012) 'An integrated socio-environmental framework for glacier hazard management and climate change adaptation: Lessons from Lake 513, Cordillera Blanca, Peru.' *Climatic Change*, 112 pp. 733–767.

Carrivick, J. L. and Tweed, F. S. (2013) 'Proglacial Lakes: Character, behaviour and geological importance.' *Quaternary Science Reviews*, 78 pp. 34–52.

Carrivick, J. L. and Tweed, F. S. (2016) 'A global assessment of the societal impacts of glacier outburst floods.' *Global and Planetary Change*, 144 pp. 1–16.

Chen, K., Blong, R. and Jacobson, C. (2001) 'MCE-RISK: Integrating multicriteria evaluation and GIS for risk decision-making in natural hazards.' *Environmental Modelling and Software*, 16(4) pp. 387–397.

Chevallier, P., Pouyaud, B., Suarez, W., and Condom, T. (2011) 'Climate change threats to environment in the tropical Andes: glaciers and water resources.' *Regional Environmental Change*, 11, pp. 179–187.

Clague, J. J. and Evans, S. G. (2000) 'A review of catastrophic drainage of moraine-dammed lakes in British Columbia . Quaternary Science Reviews A review of catastrophic drainage of moraine-dammed lakes in British Columbia.' *Quaternary Science Reviews*, 19 pp. 1763–1783.

Colonia, D., Torres, J., Haeberli, W., Schauwecker, S., Braendle, E., Giraldez, C. and Cochachin, A. (2017) 'Compiling an inventory of glacier-bed overdeepenings and potential new lakes in de-glaciating areas of the peruvian andes: Approach, first results, and perspectives for adaptation to climate Change.' *Water (Switzerland)*, 9(5).

Cook, S. J., Kougkoulos, I., Edwards, L. A., Dortch, J. and Hoffmann, D. (2016) 'Glacier change and glacial lake outburst flood risk in the Bolivian Andes.' *The Cryosphere*, 10(5) pp. 2399–2413.

Cook, S. J. and Quincey, D. J. (2015) 'Estimating the volume of Alpine glacial lakes.' *Earth Surface Dynamics*, 3 pp. 559–575.

Cook, S. J. and Swift, D. A. (2012) 'Subglacial basins: Their origin and importance in glacial systems and landscapes.' *Earth-Science Reviews*, 115 pp. 332–372.

Costa, John E., Schuster, R. E. (1988) 'The Formation and Failure of Natural Dams.' *USGS Professional Paper* pp. 1054-1068.

Coudrain, A., Francou, B. and Kundzewicz, Z. W. (2005) 'Editorial.' *Hydrological Sciences Journal*, 50(6) pp. 925–932.

Curry, A.M. and Morris, C.J. (2004) 'Lateglacial and Holocene talus slope development and rockwall retreat on Mynydd Du, UK.' *Geomorphology,* 58 pp. 85-106.

Cutter, S. L. and Finch, C. (2008) 'Temporal and spatial changes in social vulnerability to natural hazards.' *Proceedings of the National Academy of Sciences*, 105 (7) pp. 2301–2306.

Damart, S., Dias, L. C. and Mousseau, V. (2007) ‘Supporting groups in sorting decisions: Methodology and use of a multi-criteria aggregation/disaggregation DSS.’ *Decision Support Systems*, 43(4) pp. 1464–1475.

Das, S., Kar, N. S. and Bandyopadhyay, S. (2015) ‘Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images.’ *Natural Hazards*, 77(2) pp. 769–786.

Davies, B. J., Carrivick, J. L., Glasser, N. F., Hambrey, M. J. and Smellie, J. L. (2012) ‘Variable glacier response to atmospheric warming, northern Antarctic Peninsula, 1988-2009.’ *Cryosphere*, 6(5) pp. 1031–1048.

De Angelis, E. (2014) ‘Hypsometry and sensitivity of the mass balance to changes in equilibrium-line altitude : the case of the Southern Patagonia Icefield,’ 60(219) pp. 14–28.

De Brito, M. M. and Evers, M. (2016) ‘Multi-criteria decision-making for flood risk management: A survey of the current state of the art.’ *Natural Hazards and Earth System Sciences*, 16(4) pp. 1019–1033.

Diolaiuti, G. A., Maragno, D., D’Agata, C., Smiraglia, C. and Bocchiola, D. (2011) ‘Glacier retreat and climate change: Documenting the last 50 years of Alpine glacier history from area and geometry changes of Dosdè Piazzi glaciers (Lombardy Alps, Italy).’ *Progress in Physical Geography*, 35(2) pp. 161–182.

Dortch, J. M., Owen, L. a., Caffee, M. W. and Kamp, U. (2011) ‘Catastrophic partial drainage of Pangong Tso, northern India and Tibet.’ *Geomorphology*, 125(1) pp. 109–121.

Drenkhan, F., Carey, M., Huggel, C., Seidel, J. and Oré, M. T. (2015) ‘The changing water cycle : climatic and socioeconomic drivers of water-related changes in the Andes of Peru.’ *WIREs Water*, 2 pp. 715–733.

Drenkhan, F., Guardamino, L., Huggel, C. and Frey, H. (2018) ‘Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes.’ *Global and Planetary Change*, 169 pp. 105–118.

Emmer, A. (2018) ‘GLOFs in the WOS : bibliometrics , geographies and global trends of research of glacial lake outburst floods (Web of Science , 1979-2016).’ *Natural hazards and earth system sciences*, 18 pp. 813–827.

Emmer, A. (2017) ‘Geomorphologically effective floods from moraine-dammed lakes in the Cordillera Blanca , Peru.’ *Quaternary Science Reviews*. Elsevier Ltd, 177 pp. 220–234.

Emmer, A. and Cochachin, A. (2013) ‘The causes and mechanisms of moraine-dammed lake failures in the cordillera blanca, North American Cordillera, and Himalayas.’ *Acta Universitatis Carolinae, Geographica*, 48(2) pp. 5–15.

Emmer, A. and Vilímek, V. (2013) ‘Review Article: Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru).’ *Natural Hazards and Earth System Science*, 13(6) pp. 1551–1565.

Emmer, A. and Vilímek, V. (2014) ‘New method for assessing the susceptibility of glacial lakes to outburst floods in the Cordillera Blanca, Peru.’ *Hydrology and Earth System Sciences*, 18(9) pp. 3461–3479.

Emmer, A., Merkl, S. and Mergili, M. (2015) ‘Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria.’ *Geomorphology*, 246(2015) pp. 602–616.

Emmer, A., Vilímek, V., Klimeš, J. and Cochachin, A. (2014) ‘Glacier Retreat, Lakes Development and Associated Natural Hazards in Cordilera Blanca, Peru.’ *In* Shan, W., Guo, Y., Wang, F., Marui, H., and Strom, A. (eds) *Landslides in Cold Regions in the Context of Climate Change*, pp. 231–252.

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V. and Cochachin, A. (2016a) ‘882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods.’ *Catena*, 147 pp. 269–279.

Emmer, A., Vilímek, V., Huggel, C., Klimeš, J. and Schaub, Y. (2016b) ‘Limits and challenges to compiling and developing a database of glacial lake outburst floods.’ *Landslides*, (2016) pp. 1–6.

Evans, S. G. (1986) ‘The maximum discharge of outburst floods caused by the breaching of man-made and natural dams.’ *Canadian Geotechnical Journal*, 23(3) pp. 385–387.

Farinotti, D., Brinkerhoff, D. J., Clarke, G. K. C., Fürst, J. J., Frey, H., Gantayat, P., Gillet-Chaulet, F., Girard, C., Huss, M., Leclercq, P. W., Linsbauer, A., Machguth, H., Martin, C., Maussion, F., Morlighem, M., Mosbeux, C., Pandit, A., Portmann, A., Rabatel, A., Ramsankaran, R., Reerink, T. J., Sanchez, O., Stentoft, P. A., Singh Kumari, S., Van Pelt, W. J. J., Anderson, B., Benham, T., Binder, D., Dowdeswell, J. A., Fischer, A., Helfricht, K., Kutuzov, S., Lavrentiev, I., McNabb, R., Hilmar Gudmundsson, G., Li, H. and Andreassen, L. M. (2017) 'How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment.' *Cryosphere*, 11(2) pp. 949–970.

Favier, V., Wagnon, P. and Ribstein, P. (2004) 'Glaciers of the outer and inner tropics: A different behaviour but a common response to climatic forcing.' *Geophysical Research Letters*, 31(16) pp. 1–5.

Figueira, J. R., Greco, S., Roy, B. and Słowiński, R. (2013) 'An Overview of ELECTRE Methods and their Recent Extensions.' *Journal of Multi-Criteria Decision Analysis*, 20(1–2) pp. 61–85.

Francou, B., Ribstein, P., Saravia, R. and Tiriau, E. (1995) 'Monthly balance and water discharge of an inter-tropical glacier: Zongo Glacier, Cordillera Real, Bolivia, 16°S.' *Journal of Glaciology*, 41(137) pp. 61–67.

Frey, H., Huggel, C., Paul, F. and Haeberli, W. (2010) 'Automated detection of glacier lakes based on remote sensing in view of assessing associated hazard potentials.' *Proceedings 10th international symposium on high mountain remote sending cartography* pp. 23–30.

Frey, H., Huggel, C., Bühler, Y., Buis, D., Burga, M. D., Choquevilca, W., Fernandez, F., García Hernández, J., Giráldez, C., Loarte, E., Masias, P., Portocarrero, C., Vicuña, L. and Walser, M. (2016) 'A robust debris-flow and GLOF risk management strategy for a data-scarce catchment in Santa Teresa, Peru.' *Landslides* pp. 1493–1507.

Frey, H., Machguth, H., Huss, M., Huggel, C., Bajracharya, S., Bolch, T., Kulkarni, A., Linsbauer, A., Salzmann, N. and Stoffel, M. (2014) 'Estimating the volume of glaciers in the Himalayan-Karakoram region using different methods.' *Cryosphere*, 8(6) pp. 2313–2333.

Froehlich, D. C. (1995) 'Peak outflow from breached embankment dam.' *Journal of Water Resource*, 121(5766) pp. 90–97.

Fujita, K., Sakai, A., Takenaka, S., Nuimura, T., Surazakov, A. B., Sawagaki, T. and Yamanokuchi, T. (2013) 'Potential flood volume of Himalayan glacial lakes.' *Natural Hazards and Earth System Sciences*, 13(7) pp. 1827–1839.

Fujita, K., Suzuki, R., Nuimura, T. and Sakai, A. (2008) 'Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya.' *Journal of Glaciology*, 54(185) pp. 220–228.

Garcia, M., Raes, D., Jacobsen, S. E., and Michel, T. (2007) 'Agroclimatic constraints for rainfed agriculture in the Bolivian Altiplano*.' Journal of Arid Environments*, 71 pp. 109–121.

Garreaud, R. D., Vuille, M., Compagnucci, R. and Marengo, J. (2009) 'Present-day South American climate.' *Palaeogeography, Palaeoclimatology, Palaeoecology*, 281(3–4) pp. 180–195.

Grabs, W. E. and Hanisch, J. (1992) 'Objectives and Prevention Methods for Glacier Lake Outburst Moods (GLOFs).' *Snow and Glacier Hydrology*, 218 pp. 341–352.

Haeberli, W. (1983) 'Frequency characteristics of glacier floods in The Swiss Alps.' *Annals of Glaciology*, 4 pp. 85–90.

Haeberli, W. (2013) 'Mountain permafrost - research frontiers and a special long-term challenge.' *Cold Regions Science and Technology*, 96 pp. 71–76.

Haeberli W, Hallet B, Arenson L, Elconin R, Humlum O, Kääb A, Kaufmann V, Ladanyi B, Matsuoka N, Springman S, Mühll DV (2006) 'Permafrost creep and rock glacier dynamics.' *Permafrost and Periglacial Processes*, 17 pp. 189-214.

Haeberli, W., Linsbauer, A., Cochachin, A., Salazar, C. and Fischer, U. H. (2016) 'On the morphological characteristics of overdeepenings in high-mountain glacier beds.' *Earth Surface Processes and Landforms*, 41(13) pp. 1980–1990.

Haeberli, W., Schaub, Y. and Huggel, C. (2017) 'Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges.' *Geomorphology*, 293 pp. 405–417.

Haemmig, C., Huss, M., Keusen, H., Hess, J., Wegmüller, U., Ao, Z. and Kulubayi, W. (2014) 'Hazard assessment of glacial lake outburst floods from Kyagar glacier, Karakoram mountains, China.' *Annals of Glaciology*, 55(66) pp. 34–44.

Hanshaw, M. N. and Bookhagen, B. (2014) 'Glacial areas, lake areas, and snow lines from 1975 to 2012: Status of the cordillera vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru.' *Cryosphere*, 8(2) pp. 359–376.

Hegglin, E. and Huggel, C. (2008) 'An Integrated Assessment of Vulnerability to Glacial Hazards.' *Mountain Research and Development*, 28(3) pp. 299–309.

Hill, L. J., Sparks, R. S. and Rougier, J. C. (2012) *Risk assessment and uncertainty in natural hazards*.

Hino, M., Field, C. B. and Mach, K. J. (2017) 'Managed retreat as a response to natural hazard risk.' *Nature Climate Change*, 7(5) pp. 364–370.

Hoffmann, D., Weggenmann, D. (2013) 'Climate Change Induced Glacier Retreat and Risk Management: Glacial Lake Outburst Floods (GLOFs) in the Apolobamba Mountain Range, Bolivia.' *Climate change and disaster risk management,* pp. 71-87.

Houston, J. and Hartley, A. J. (2003) 'The central andean west-slope rainshadow and its potential contribution to the origin of hyper-aridity in the Atacama Desert.' *International Journal of Climatology*, 23(12) pp. 1453–1464.

Huang, I. B., Keisler, J. and Linkov, I. (2011) 'Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends.' *Science of the Total Environment*, 409(19) pp. 3578–3594.

Hubbard, B., Heald, A., Reynolds, J. M., Quincey, D., Richardson, S. D., Luyo, M. Z., Portilla, N. S. and Hambrey, M. J. (2005) 'Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru.' *Earth Surface Processes and Landforms*, 30(10) pp. 1251–1264.

Huggel, C., Haeberli, W., Kääb, A., Bieri, D. and Richardson, S. (2004) 'An assessment procedure for glacial hazards in the Swiss Alps.' *Canadian Geotechnical Journal*, 41 pp. 1068–1083.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P. and Paul, F. (2002) 'Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps.' *Canadian Geotechnical Journal*, 39(2) pp. 316–330.

Huggel, C., Muccione, V., Carey, M., James, R., Jurt, C. and Mechler, R. (2018) 'Loss and Damage in the mountain cryosphere.' *Regional Environmental Change*

Huggel, C., Wallimann-helmer, I., Stone, D. and Cramer, W. (2016) 'Reconciling justice and attribution research to advance climate policy.' *Nature Climate Change*, 6(10) pp. 901–908.

Huss, M., Bauder, A., Werder, M., Funk, M. and Hock, R. (2007) 'Glacier-dammed lake outburst events of Gornersee, Switzerland.' *Journal of Glaciology*, 53(181) pp. 189–200.

ICIMOD. 2011. Glacial lakes and glacial lake outburst floods in Nepal. International Centre for Integrated Mountain Development (ICIMOD): Kathmandu.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Ishizaka, A., Pearman, C. and Nemery, P. (2012) 'AHPSort: an AHP-based method for sorting problems.' *International Journal of Production Research*, 50(17) pp. 4767–4784.

ISO 31000:2009 (2009) Risk management - Principles and guidelines. International Organization for Standardization, Geneva, Switzerland.

ISO 31000:2018 (2018) Risk management - Principles and guidelines. International Organization for Standardization, Geneva, Switzerland.

Iturrizaga, L. 2014. Glacial and glacially conditioned lake types in the Cordillera Blanca, Peru: A spatiotemporal conceptual approach. *Progress in Physical Geography*, 38 (5) pp. 602–636.

Ives, JD., Shrestha, RB., Mool, PK. (2010) 'Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment.' ICIMOD: Kathmandu.

Jakob, M., Stein, D. and Ulmi, M. (2012) ‘Vulnerability of buildings to debris flow impact.’ *Natural Hazards*, 60(2) pp. 241–261.

Janke, J. R., Bellisario, A. C. and Ferrando, F. A. (2015) ‘Geomorphology Classi fi cation of debris-covered glaciers and rock glaciers in the Andes of central Chile.’ *Geomorphology*, 241 pp. 98–121.

Janský, B., Šobr, M., Engel, Z. (2010) ‘Outburst flood hazard: Case studies from the Tien-Shan Mountains, Kyrgyzstan.’ *Limnologica*, 40(4) pp. 358–364.

Janssen, M., Lee, J., Bharosa, N. and Cresswell, A. (2010) ‘Advances in multi-agency disaster management: Key elements in disaster research.’ *Information Systems Frontiers*, 12(1) pp. 1–7.

Jennings, S. (2011) ‘Time’s Bitter Flood disasters: trends in the number of reported natural disasters.’ *Oxfam Research Report* p. 33.

Jiskoot, H., Curran, C. J., Tessler, D. L. and Shenton, L. R. (2009) ‘Changes in Clemenceau Icefield and Chaba Group glaciers , Canada , related to hypsometry , tributary detachment , length – slope and area – aspect relations.’ *Annals of Glaciology*, 50(53) pp. 133–143.

Jordan, E., Brockman, C., Fernandez, A., Alvarez, R. and Jacobsen, K. (1980) ‘The glacier inventory of Bolivia.’ *World glacier inventory*, 126(126) pp. 25–32.

Kaenzig, R. (2015) ‘Can glacial retreat lead to migration? A critical discussion of the impact of glacier shrinkage upon population mobility in the Bolivian Andes.’ *Population and Environment*, 36 pp. 480–496

Kapitsa, V., Shahgedanova, M., MacHguth, H., Severskiy, I. and Medeu, A. (2017) ‘Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling.’ *Natural Hazards and Earth System Sciences*, 17(10) pp. 1837–1856.

Kaser, G. (1999) ‘A review of the modern fluctuations of tropical glaciers.’ *Global and Planetary Change*, 22(1-4) pp. 93–103.

Kaser, G., Georges, C., Juen, I. and Mölg, T. (2005) 'Low Latitude Glaciers: Unique Global Climate Indicators and Essential Contributors to Regional Fresh Water Supply. A Conceptual Approach.' *Global Change and Mountain Regions* pp. 185–195.

Kaser, G., Osmaston,H. (2002) 'Tropical glaciers.' *New York: Cambridge University Press.*

Khanal, N. R., Mool, P. K., Shrestha, A. B., Rasul, G., Ghimire, P. K., Shrestha, R. B. and Joshi, S. P. (2015) 'A comprehensive approach and methods for glacial lake outburst flood risk assessment, with examples from Nepal and the transboundary area.' *International Journal of Water Resources Development*, 31(2) pp. 219–237.

Kingslake, J. (2013) 'Modelling ice-dammed lake drainage' PhD Thesis

Kingslake, J. and Ng, F. (2013) 'Modelling the coupling of flood discharge with glacier flow during jökulhlaups.' *Annals of Glaciology*, 54(63) pp. 25–31.

Kingslake, J. (2015) 'Chaotic dynamics of a glaciohydraulic model.' *Journal of Glaciology*, 61(227) pp. 493–502.

Klimeš, J., Benešová, M., Vilímek, V., Bouška, P. and Cochachin Rapre, A. (2014) 'The reconstruction of a glacial lake outburst flood using HEC-RAS and its significance for future hazard assessments: an example from Lake 513 in the Cordillera Blanca, Peru.' *Natural Hazards*, 71(3) pp. 1617–1638.

Komori, J. (2008) 'Recent expansions of glacial lakes in the Bhutan Himalayas.' *Quaternary International*, 184(1) pp. 177–186.

Korup, O. and Tweed, F. (2007) 'Ice, moraine, and landslide dams in mountainous terrain.' *Quaternary Science Reviews*, 26(25-28) pp. 3406–3422.

Kougkoulos, I., Cook, S. J., Edwards, L. A., Clarke, L. J., Symeonakis, E., Dortch, J. M. and Nesbitt, K. (2018b) 'Modelling glacial lake outburst flood impacts in the Bolivian Andes.' *Natural Hazards*, 94(3) pp. 1415–1438.

Kougkoulos, I., Cook, S. J., Jomelli, V., Clarke, L., Symeonakis, E., Dortch, J. M., Edwards, L. A. and Merad, M. (2018a) 'Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes.' *Science of the Total Environment*, 621 pp. 1453–1466.

Kropáček, J., Neckel, N., Tyrna, B., Holzer, N., Hovden, A., Gourmelen, N., Schneider, C., Buchroithner, M. and Hochschild, V. (2015) 'Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in north-western Nepal.' *Natural Hazards and Earth System Sciences*, 15(10) pp. 2425–2437.

Lala, J. M., Rounce, D. R. and Mckinney, D. C. (2017) 'Modeling the Glacial Lake Outburst Flood Process Chain in the Nepal Himalaya : Reassessing Imja Tsho ' s Hazard.' *Hydrology and Earth System Sciences Discussions*, (December) pp. 1–25.

Levitus, S. (2001) 'Anthropogenic Warming of Earth Climate System.' *Science (New York, N.Y.)*, 292, pp. 267–270.

Lin, W. T. (2008) 'Earthquake-induced landslide hazard monitoring and assessment using SOM and PROMETHEE techniques: A case study at the Chiufenershan area in Central Taiwan.' *International Journal of Geographical Information Science*, 22(15) pp. 995–1012.

Linsbauer, A., Frey, H., Haeberli, W., Machguth, H., Azam, M. F. and Allen, S. (2016) 'Modelling glacier-bed overdeepenings and possible future lakes for the glaciers in the Himalaya-Karakoram region.' *Annals of Glaciology*, 57(71) pp. 119–130.

Linsbauer, A., Paul, F. and Haeberli, W. (2012) 'Modeling glacier thickness distribution and bed topography over entire mountain ranges with glabtop: Application of a fast and robust approach.' *Journal of Geophysical Research: Earth Surface*, 117(3) pp. 1–17.

López-Moreno, J. I., Fontaneda, S., Bazo, J., Revuelto, J., Azorin-Molina, C., Valero-Garcés, B., Morán-Tejeda, E., Vicente-Serrano, S. M., Zubieta, R. and Alejo-Cochachín, J. (2014) 'Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru.' *Global and Planetary Change*, 112 pp. 1–11.

Malczewski, J. and Rinner, C. (2015) *Multicriteria Decision Analysis in Geographic Information Science*. *Analysis methods*.

Marinoni, O. (2005) 'A stochastic spatial decision support system based on PROMETHEE.' *International Journal of Geographical Information Science*, 19(1) pp. 51–68.

Mark, B. G., McKenzie, J. M. and Gómez, J. (2005) 'Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge: Callejon de Huaylas, Peru.' *Hydrological Sciences Journal*, 50(6) pp. 975–988.

Mark, B. G. and Seltzer, G. O. (2003) 'Tropical glacier meltwater contribution to stream discharge: a case study in the Cordillera Blanca.' *Peruvian Journal of Glaciology*, 49 pp. 271–281.

McDowell, J. Z. and Hess, J. J. (2012) 'Accessing adaptation : Multiple stressors on livelihoods in the Bolivian highlands under a changing climate.' *Global Environmental Change*, 22(2) pp. 342–352.

McKillop, R. J. and Clague, J. J. (2007a) 'Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia.' *Global and Planetary Change*, 56(1-2) pp. 153–171.

McKillop, R. J. and Clague, J. J. (2007b) 'A procedure for making objective preliminary assessments of outburst flood hazard from moraine-dammed lakes in southwestern British Columbia.' *Natural Hazards*, 41(1) pp. 131–157.

Merad, M. M., Verdel, T., Roy, B. and Kouniali, S. (2004) 'Use of multi-criteria decision-aids for risk zoning and management of large area subjected to mining-induced hazards.' *Tunnelling and Underground Space Technology*, 19(2) pp. 125–138.

Mergili, M., Emmer, A., Juřicová, A., Cochachin, A., Fischer, J. T., Huggel, C. and Pudasaini, S. P. (2018) 'How well can we simulate complex hydro-geomorphic process chains? The 2012 multi-lake outburst flood in the Santa Cruz Valley (Cordillera Blanca, Perú).' *Earth Surface Processes and Landforms*.

Mergili, M. and Schneider, J. F. (2011) 'Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS.' *Natural Hazards and Earth System Science*, 11(5) pp. 1447–1462.

Mertes, J. R., Thompson, S. S., Booth, A. D., Gulley, J. D. and Benn, D. I. (2016) 'A conceptual model of supraglacial lake formation on debris-covered glaciers based on GPR facies analysis.' *Earth Surface Processes and Landforms*.

Messerli B. (2001) 'The International Year of Mountains.' The Mountain Research Initiative and PAGES. PAGES Newsletter 1:2.

Mitchell, J.F.B., Lowe, J.A., Wood, R.A., et al. (2006) 'Extreme events due to human-induced climate change.' *Philosophical Transactions of the Royal Society*, 364, pp. 2117–2133.

Mitchell, T., and van Aalst, M.K. (2008) 'Convergence of Disaster Risk Reduction and Climate Change Adaptation: A Review for DFID.' Department for International Development (DFID), London, UK.

Moe, T. L. and Pathranarakul, P. (2006) 'An integrated approach to natural disaster management.' *Disaster Prevention and Management*, 15(3) p. 396.

Mousseau, V., Slowinski, R. and Zielniewicz, P. (2000) 'A user-oriented implementation of the ELECTRE-TRI method integrating preference elicitation support.' *Computers and Operations Research*, 27 pp. 757–777.

Nemery, P. and Lamboray, C. (2008) 'Flow sort: A flow-based sorting method with limiting or central profiles.' *Top*, 16(1) pp. 90–113.

Ng, F. and Björnsson, H. (2003) 'On the Clague-Mathews relation for j??kulhlaups.' *Journal of Glaciology*, 49(165) pp. 161–172.

Nie, Y., Sheng, Y., Liu, Q., Liu, L., Liu, S., Zhang, Y. and Song, C. (2017) 'A regional-scale assessment of Himalayan glacial lake changes using satellite observations from 1990 to 2015.' *Remote Sensing of Environment*, 189 pp. 1–13.

O'Connor, J. E., Hardison III, J. H. and Costa, J. E. (2001) *Debris Flows from Failures of Neoglacial- Age Moraine Dams in the Three Sisters and Mount Jefferson Wilderness Areas, Oregon*. *USGS Professional Paper*.

Omelicheva, M. Y. (2011) 'Natural Disasters: Triggers of Political Instability?' *International Interactions*, 37(4) pp. 441–465.

Oxfam International Report (2009) Climate change, poverty and adaptation.

Painter, J. (2007) 'Deglaciation in the Andean Region, Human Development Report 2007/2008: Fighting climate change: Human solidarity in a divided world.' *Human Development Report Office, Occasional Paper,* 2007/55, pp. 1-21

Paul, F. and Linsbauer, A. (2012) 'Modeling of glacier bed topography from glacier outlines, central branch lines, and a DEM.' *International Journal of Geographical Information Science*, 26(7) pp. 1173–1190.

Paul, F., Barrand, N. E., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S. P., Konovalov, V., Bris, R. Le, Mölg, N., Nosenko, G., Nuth, C., Pope, A., Racoviteanu, A., Rastner, P., Raup, B., Scharrer, K., Steffen, S. and Winsvold, S. (2013) 'On the accuracy of glacier outlines derived from remote-sensing data.' *Annals of Glaciology*, 54 pp. 171–182.

Petrakov, D. A., Tutubalina, O. V., Aleinikov, A. A., Chernomorets, S. S., Evans, S. G., Kidyaeva, V. M., Krylenko, I. N., Norin, S. V., Shakhmina, M. S. and Seynova, I. B. (2012) 'Monitoring of Bashkara Glacier lakes (Central Caucasus, Russia) and modelling of their potential outburst.' *Natural Hazards*, 61(3) pp. 1293–1316.

Petrov, M. A., Sabitov, T. Y., Tomashevskaya, I. G., Glazirin, G. E., Chernomorets, S. S., Savernyuk, E. A., Tutubalina, O. V., Petrakov, D. A., Sokolov, L. S., Dokukin, M. D., Mountrakis, G., Ruiz-Villanueva, V. and Stoffel, M. (2017) 'Glacial lake inventory and lake outburst potential in Uzbekistan.' *Science of The Total Environment*, 592 pp. 228–242.

Pierce, M. W., Thornton, C. I. and Abt, S. R. (2010) 'Predicting Peak Outflow from Breached Embankment Dams.' *Journal of Hydrologic Engineering*, 15(5) pp. 338–349.

Pitman, E. B., Patra, A. K., Kumar, D., Nishimura, K. and Komori, J. (2013) 'Two phase simulations of glacier lake outburst flows.' *Journal of Computational Science*, 4(1–2) pp. 71–79.

Prakash, C. and Nagarajan, R. (2017) 'Outburst susceptibility assessment of moraine-dammed lakes in Western Himalaya using an analytic hierarchy process.' *Earth Surface Processes and Landforms*, 42(July) pp. 2306–2321.

Purdy, G. (2010) 'ISO 31000:2009 - Setting a new standard for risk management: Perspective.' *Risk Analysis*, 30(6) pp. 881–886.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Ménégoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M. and Wagnon, P. (2013) 'Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change.' *Cryosphere*, 7(1) pp. 81–102.

Racoviteanu, A. E., Arnaud, Y., Williams, M. W. and Ordoñez, J. (2008) 'Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing.' *Journal of Glaciology*, 54(186) pp. 499–510.

Rangecroft, S., Harrison, S., Anderson, K., Magrath, J., Castel, A. P. and Pacheco, P. (2013) 'Climate Change and Water Resources in Arid Mountains: An Example from the Bolivian Andes.' *Ambio*, 42(7) pp. 852–863.

Rangecroft, S., Harrison, S., Anderson, K., Magrath, J., Castel, A. P. and Pacheco, P. (2014) 'Short Communication A First Rock Glacier Inventory for the Bolivian Andes.' *Permafrost and Periglacial Processes*, 25 pp. 333–343.

Rangecroft, S., Suggitt, A. J., Anderson, K. and Harrison, S. (2016) 'Future climate warming and changes to mountain permafrost in the Bolivian Andes.' *Climatic Change*, 137 pp. 231–243.

Raoul, K. (2014) 'Can glacial retreat lead to migration? A critical discussion of the impact of glacier shrinkage upon population mobility in the Bolivian Andes.' *Population and Environment*, 36(4) pp. 480–496.

Rashid, I. and Majeed, U. (2018) 'Recent recession and potential future lake formation on Drang Drung glacier, Zanskar Himalaya, as assessed with earth observation data and glacier modelling.' *Environmental Earth Sciences*. Springer Berlin Heidelberg, 77(12) pp. 1–13.

Reese, S., Cousins, W. J., Power, W. L., Palmer, N. G., Tejakusuma, I. G. and Nugrahadi, S. (2007) 'Tsunami vulnerability of buildings and people in South Java - field observations after the July 2006 Java tsunami.' *Natural Hazards and Earth System Science*, 7(5) pp. 573–589.

Reynolds, J. M. (2003) Development of glacial hazard and risk minimisation protocols in rural environments Methods of glacial hazard assessment and management in the Cordillera Blanca *, Project No : R7816 . H*.

Richardson, S. D. and Reynolds, J. M. (2000) 'An overview of glacial hazards in the Himalayas.' *Quaternary International*, 65-66 pp. 31–47.

Rickenmann, D. (1999) 'Empirical relationships for debris flows.' *Natural Hazards*, 19(1) pp. 47–77.

Rickenmann, D. (2005) 'Runout prediction methods.' *Debris-flow Hazards and Related Phenomena* pp. 305–324.

Rivas, D. S., Somos-Valenzuela, M. A., Hodges, B. R. and McKinney, D. C. (2015) 'Predicting outflow induced by moraine failure in glacial lakes: The Lake Palcacocha case from an uncertainty perspective.' *Natural Hazards and Earth System Sciences*, 15(6) pp. 1163–1179.

Rivera A., Cawkwell F., Rada C., Bravo C. (2011) Hypsometry. In: Singh V.P., Singh P., Haritashya U.K. (eds) Encyclopedia of Snow, Ice and Glaciers. Encyclopedia of Earth Sciences Series.

Röhl, K. (2008) 'Characteristics and evolution of supraglacial ponds on debris-covered Tasman Glacier, New Zealand.' *Journal of Glaciology*, 54(188) pp. 867–880.

Rounce, D. R., McKinney, D. C., Lala, J. M., Byers, A. C. and Watson, C. S. (2016) 'A New Remote Hazard and Risk Assessment Framework for Glacial Lakes in the Nepal Himalaya.' *Hydrology and Earth System Sciences Discussions*, 20, pp. 3455–3475.

Rounce, D. R., Byers, A. C., Byers, E. A. and McKinney, D. C. (2017a) 'Brief communication: Observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal.' *Cryosphere*, 11(1) pp. 443–449.

Rounce, D., Watson, C. and McKinney, D. (2017b) 'Identification of Hazard and Risk for Glacial Lakes in the Nepal Himalaya Using Satellite Imagery from 2000–2015.' *Remote Sensing*, 9(7) p. 654.

Roy, B. (1993) 'Decision science or decision aid science?' *European Journal of Operational Research*, 66 pp. 184–203.

Roy, B. (1996) '*Multicriteria methodology for decision analysis*.' Kluwer, Dordrecht. Original version in French '*Méthodologie multicritère d'aide à la décision*.' Economica, Paris, 1985.

Saaty, T. L. (1977) 'A scaling method for priorities in hierarchical structures.' *Journal of Mathematical Psychology*, 15(3) pp. 234–281.

Sakai, A., Chikita, K. and Yamada, T. (2000) 'Expansion of a moraine-dammed glacial lake, Tsho Rolpa, in Rolwaling Himal, Nepal Himalaya.' *Limnology and Oceanography*, 45(6) pp. 1401–1408.

Saltelli, A., Tarantola, S. and Chan, K. (1999) 'A Role for Sensitivity Analysis in Presenting the Results from MCDA Studies to Decision Makers.' *Journal of Multi-Criteria Decision Analysis*, 145(April) pp. 139–145.

Sánchez-Lozano, J. M., Henggeler Antunes, C., García-Cascales, M. S. and Dias, L. C. (2014) 'GIS-based photovoltaic solar farms site selection using ELECTRE-TRI: Evaluating the case for Torre Pacheco, Murcia, Southeast of Spain.' *Renewable Energy*, 66 pp. 478–494.

Society for Risk analysis (SRA) glossary, June 22, 2015

Schauwecker, S., Rohrer, M., Huggel, C., Endries, J., Montoya, N., Neukom, R., Perry, B., Salzmann, N., Schwarb, M. and Suarez, W. (2017) 'The freezing level in the tropical Andes,Peru : an indicator for present and future glacier extents.' *Journal of Geophysical Research: Atmospheres*, 122 pp. 5172–5189.

Sicart, J. E., Wagnon, P. and Ribstein, P. (2005) 'Atmospheric controls of the heat balance of Zongo Glacier (16°S, Bolivia).' *Journal of Geophysical Research: Atmospheres*, 110(12) pp. 1–17.

Somos-Valenzuela, M. A., Chisolm, R. E., Rivas, D. S., Portocarrero, C. and McKinney, D. C. (2016) 'Modeling glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru.' *Hydrology and Earth System Sciences Discussions*, 2010 pp. 1–61.

Somos-Valenzuela, M. A., McKinney, D. C., Byers, A. C., Rounce, D. R., Portocarrero, C. and Lamsal, D. (2015) 'Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal.' *Hydrology and Earth System Sciences*, 19(3) pp. 1401–1412.

Somos-Valenzuela, M. A., McKinney, D. C., Rounce, D. R. and Byers, A. C. (2014) 'Changes in Imja Tsho in the Mount Everest region of Nepal.' *Cryosphere*, 8(5) pp. 1661–1671.

Soruco, A., Vincent, C., Francou, B. and Gonzalez, J. F. (2009) ‘Glacier decline between 1963 and 2006 in the Cordillera Real, Bolivia.’ *Geophysical Research Letters*, 36(3) pp. 2–7.

Soruco, A., Vincent, C., Rabatel, A., Francou, B., Thibert, E., Sicart, J. E. and Condom, T. (2015) ‘Contribution of glacier runoff to water resources of La Paz city, Bolivia (16°S).’ *Annals of Glaciology*, 56(70) pp. 147–154.

Squeo, F. A.,Warner, B., Aravena, R., and Espinoza, D. (2006) Bofedales: high altitude peatlands of the central Andes.’ *Revista Chilena de Historia Natural,*79 pp. 245–255.

Stecchi, F., Mancini, F., Ceppi, C. and Gabbianelli, G. (2012) ‘Vulnerability to ground deformation phenomena in the city of Tuzla (BiH): A GIS and multicriteria approach.’ *Natural Hazards*, 64(3) pp. 2153–2165.

Stokes, C. R., Popovnin, V., Aleynikov, A., Gurney, S. D. and Shahgedanova, M. (2007) ‘Recent glacier retreat in the Caucasus Mountains, Russia, and associated increase in supraglacial debris cover and supra-/proglacial lake development.’ *Annals of Glaciology*, 46(1).

Tacnet, J. M., Dezert, J., Curt, C., Batton-Hubert, M. and Chojnacki, E. (2014) ‘How to manage natural risks in mountain areas in a context of imperfect information? New frameworks and paradigms for expert assessments and decision-making.’ *Environment Systems and Decisions*, 34(2) pp. 288–311.

Tervonen, T. (2012) ‘JSMAA: open source software for SMAA computations.’ *International Journal of Systems Science*, 45(1) pp. 69–81.

Thompson, L. G., Mosley-Thompson, E., Brecher, H., Davis, M., León, B., Les, D., Lin, P.-N., Mashiotta, T. and Mountain, K. (2006) ‘Abrupt tropical climate change: Past and present.’ *Proceedings of the National Academy of Sciences*, 103(28) pp. 10536–10543.

Thompson, S. S., Benn, D. I., Dennis, K. and Luckman, A. (2012) ‘A rapidly growing moraine-dammed glacial lake on Ngozumpa Glacier, Nepal.’ *Geomorphology*, 145, pp.1–11.

Tsutaki, S., Nishimura, D., Yoshizawa, T. and Sugiyama, S. (2011) ‘Changes in glacier dynamics under the influence of proglacial lake formation in Rhonegletscher , Switzerland.’ *Annals of Glaciology*, 52(58) pp. 31–36.

Truffer, M. and Motyka, R. J. (2016) 'Reviews of Geophysics Where glaciers meet water : Subaqueous melt and its relevance to glaciers in various settings.' *Reviews of Geophysics*, 54 pp. 220–239.

Tweed, F. S. and Russell, A. J. (1999) 'Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics.' *Progress in Physical Geography*, 23(1) pp. 79–110.

United Nations Environment Programme (UNEP), 2014. Where will the water go? Impacts of accelerated glacier melt in the Tropical Andes Article reproduced from United Nations Environment Programme (UNEP) Global Environmental Alert Service (GEAS), 10 pp.108–119.

United Nations Office for Disaster Risk Reduction (UNISDR) annual report 2015

Urrutia, R. and Vuille, M. (2009) 'Climate change projections for the tropical Andes using a regional climate model: Temperature and precipitation simulations for the end of the 21st century.' *Journal of Geophysical Research Atmospheres*, 114(2) pp. 1–15.

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, T. Murray, F. Paul, J. Ren, E. Rignot, O. Solomina, K. Steffen and T. Zhang, 2013: Observations: Cryosphere. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.

Veettil, B. K., Bremer, U. F., de Souza, S. F., Maier, É. L. B. and Simões, J. C. (2016) 'Influence of ENSO and PDO on mountain glaciers in the outer tropics: case studies in Bolivia.' *Theoretical and Applied Climatology*. Theoretical and Applied Climatology, 125(3-4) pp. 757–768.

Veettil, B. K., Wang, S., Simões, J. C. and Pereira, S. F. R. (2018) 'Glacier monitoring in the eastern mountain ranges of Bolivia from 1975 to 2016 using Landsat and Sentinel-2 data.' *Environmental Earth Sciences*, 77(12) pp. 1–14.

Vehling, L., Baewert, H., Glira, P., Moser, M., Rohn, J. and Morche, D. (2017) 'Quantification of sediment transport by rockfall and rockslide processes on a proglacial rock slope (Kaunertal, Austria).' *Geomorphology*, 287 pp. 46–57.

Vergara, W., Deeb, A. M., Valencia, A. M., Bradley, R. S., Francou, B., Zarzar, A., Grünwaldt, A. and Haeussling, S. M. (2007) 'Economic Impacts of Rapid Glacier Retreat in the Andes.' *Eos, Transactions American Geophysical Union*, 88(25) p. 261.

Vilímek, V., Emmer, A., Huggel, C., Schaub, Y. and Sara Würmli (2013) 'Database of glacial lake outburst floods (GLOFs)-IPL project No. 179.' *Landslides*, 11(1) pp. 161–165.

Vilímek, V., Klimeš, J., Emmer, A. and Benešová, M. (2015) 'Geomorphologic impacts of the glacial lake outburst flood from Lake No . 513 (Peru).' *Environmental Earth Sciences*, 73(9) pp. 5233–5244.

Vincent, C., Auclair, S. and Meur, E. Le (2010) 'Outburst flood hazard for glacier-dammed lac de Rochemelon, France.' *Journal of Glaciology*, 56(195) pp. 91–100.

Vuichard, D. and Zimmermann, M. (1986) 'The Langmoche Flash-Flood, Khumbu Himalaya, Nepal.' *Mountain Research and Development*, 6(1) pp. 90–94.

Vuille, M., Carey, M., Huggel, C., Buytaert, W., Rabatel, A., Jacobsen, D., Soruco, A., Villacis, M., Yarleque, C., Elison Timm, O., Condom, T., Salzmann, N. and Sicart, J. E. (2018) 'Rapid decline of snow and ice in the tropical Andes – Impacts, uncertainties and challenges ahead.' *Earth-Science Reviews*, 176 pp. 195–213.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G. and Bradley, R. S. (2008) 'Climate change and tropical Andean glaciers: Past, present and future.' *Earth-Science Reviews*, 89(3-4) pp. 79–96.

Vuille, M., Franquist, E., Garreaud, R., Sven, W., Casimiro, L. and Cáceres, B. (2015) 'Impact of the global warming hiatus on Andean temperature.' *Journal of Geophysical Research: Atmospheres*, 120 pp. 3745–3757.

Walder, J. S. and Costa, J. E. (1996) 'Outburst Floods From Glacier-Dammed Lakes: the Effect of Mode of Lake Drainage on Flood Magnitude.' *Earth Surface Processes and Landforms*, 21(8) pp. 701–723.

Wang, S., Qin, D. and Xiao, C. (2015a) 'Moraine-dammed lake distribution and outburst flood risk in the Chinese Himalaya.' *Journal of Glaciology*, 61(225) pp. 115–126.

Wang, W., Gao, Y., Iribarren Anacona, P., Lei, Y., Xiang, Y., Zhang, G., Li, S. and Lu, A. (2015b) 'Integrated hazard assessment of Cirenmaco glacial lake in Zhangzangbo valley, Central Himalayas.' *Geomorphology*.

Wang, W., Xiang, Y., Gao, Y., Lu, A., Yao, T. (2015c) 'Rapid expansion of glacial lakes caused by climate and glacier retreat in the Central Himalayas.' *Hydrological Processes,* 29(6) pp.859–874.

Wang, W., Yang, X. and Yao, T. (2012b) 'Evaluation of ASTER GDEM and SRTM and their suitability in hydraulic modelling of a glacial lake outburst flood in southeast Tibet.' *Hydrological Processes*, 26(2) pp. 213–225.

Wang, W., Yao, T., Gao, Y., Yang, X. and Kattel, D. B. (2011) 'A First-order Method to Identify Potentially Dangerous Glacial Lakes in a Region of the Southeastern Tibetan Plateau.' *Mountain Research and Development*, 31(2) pp. 122–130.

Wang, X., Ding, Y., Liu, S., Jiang, L., Wu, K., Jiang, Z. and Guo, W. (2013) 'Changes of glacial lakes and implications in Tian Shan, central Asia, based on remote sensing data from 1990 to 2010.' *Environmental Research Letters*, 8(4) pp. 1–11.

Wang, X., Liu, S., Ding, Y., Guo, W., Jiang, Z., Lin, J. and Han, Y. (2012a) 'An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data.' *Natural Hazards and Earth System Science*, 12(10) pp. 3109–3122.

Wang, X., Liu, S., Guo, W. and Xu, J. (2008) 'Assessment and Simulation of Glacier Lake Outburst Floods for Longbasaba and Pida Lakes, China.' *Mountain Research and Development*, 28(3) pp. 310–317.

Watanabe, T., Lamsal, D. and Ives, J. D. (2009) 'Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja Glacier, Khumbu Himal, Nepal.' *Norsk Geografisk Tidsskrift - Norwegian Journal of Geography*, 63(4) pp. 255–267.

Watson, C. S., Carrivick, J. and Quincey, D. (2015) ‘An improved method to represent DEM uncertainty in glacial lake outburst flood propagation using stochastic simulations.’ *Journal of Hydrology*, 529 pp. 1373–1389.

Westoby, M. J., Glasser, N. F., Brasington, J., Hambrey, M. J., Quincey, D. J. and Reynolds, J. M. (2014a) ‘Modelling outburst floods from moraine-dammed glacial lakes.’ *Earth-Science Reviews*, 134 pp. 137–159.

Westoby, M. J., Glasser, N. F., Hambrey, M. J., Brasington, J., Reynolds, J. M. and Hassan, M. A. A. M. (2014b) ‘Reconstructing historic glacial lake outburst floods through numerical modelling and geomorphological assessment: Extreme events in the Himalaya.’ *Earth Surface Processes and Landforms*, 39(12) pp. 1675–1692.

Wilk, J., Jonsson, A. C., Rydhagen, B., del Callejo, I., Cerruto, N., Chila, G., Encinas, S., Kumar, A. and Rani, A. (2018) ‘Assessing vulnerability in Cochabamba, Bolivia and Kota, India: how do stakeholder processes affect suggested climate adaptation interventions?’ *International Journal of Urban Sustainable Development*, 10(1) pp. 32–48.

Williams, G. P. (1978) ‘Bank-full discharge of rivers.’ *Water Resources Research*, 14(6) pp. 1141–1154.

Wilson, R., Glasser, N. F., Reynolds, J. M., Harrison, S., Anacona, P. I., Schaefer, M. and Shannon, S. (2018) ‘Glacial lakes of the Central and Patagonian Andes.’ *Global and Planetary Change*, 162 pp. 275–291.

Wisner, B., Blaikie, P., Cannon, T., Davis, I. (2004) At Risk: Natural Hazards, people vulnerability and disasters, *Routledge,* 2nd edition, pp. 496.

Wood, N., (2011) ‘Understanding risk and resilience to natural hazards: U.S. Geological Survey Fact Sheet’ 2011-3008, 2 p.

World Bank Annual Report (2010)

World Disasters Report (IFRC) (2014)

Worni, R., Huggel, C. and Stoffel, M. (2013) ‘Glacial lakes in the Indian Himalayas--from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes.’ *The Science of the total environment*, 468-469 pp. S71–84.

Worni, R., Stoffel, M., Huggel, C., Volz, C., Casteller, A. and Luckman, B. (2012) 'Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina).' *Journal of Hydrology*, 444–445 pp. 134–145.

Yarleque, C., Vuille, M., Hardy, D. R., Timm, O. E., De la Cruz, J., Ramos, H. and Rabatel, A. (2018) 'Projections of the future disappearance of the Quelccaya Ice Cap in the Central Andes.' *Scientific Reports*, 8(1) p. 15564.

Zapata, M. L. (2002) 'La dinamica glaciar en lagunas de la Cordillera Blanca.' *Acta Montana,* 19 pp. 37 -60

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S. U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A. P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L. N., Càceres, B. E., Casassa, G., Cobos, G., Dàvila, L. R., Delgado Granados, H., Demuth, M. N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J. O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V. V., Portocarrero, C. A., Prinz, R., Sangewar, C. V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R. and Vincent, C. (2015) 'Historically unprecedented global glacier decline in the early 21st century.' *Journal of Glaciology*, 61(228) pp. 745–762.

Appendices

Appendix 1.1.

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Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes

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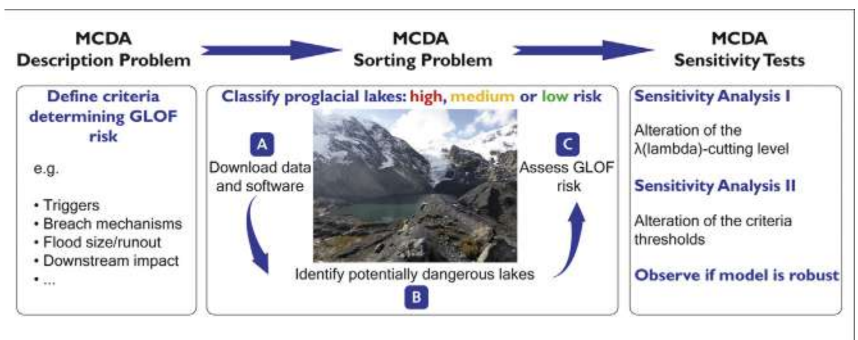
HIGHLIGHTS

- First use of multi-criteria decision analysis for glacial lake outburst flood risk
- Method uses free and widely available data and software without need for fieldwork.
- Method can be applied to any region of the world and to any glacial lake type.
- Sensitivity analyses and comparison to previous work demonstrate robust results.
- Method applied to Bolivia, illustrates three lakes as medium/high risk.

GRAPHICAL ABSTRACT



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ABSTRACT

Glacial Lake Outburst Floods (GLOFs) represent a significant threat in deglaciating environments, necessitating the development of GLOF hazard and risk assessment procedures. Here, we outline a Multi-Criteria Decision Analysis (MCDA) approach that can be used to rapidly identify potentially dangerous lakes in regions without existing tailored GLOF risk assessments, where a range of glacial lake types exist, and where field data are sparse or non-existent. Our MCDA model (1) is desk-based and uses freely and widely available data inputs and software, and (2) allows the relative risk posed by a range of glacial lake types to be assessed simultaneously within any region. A review of the factors that influence GLOF risk, combined with the strict rules of criteria selection inherent to MCDA, has allowed us to identify 13 exhaustive, non-redundant, and consistent risk criteria. We use our MCDA model to assess the risk of 16 extant glacial lakes and 6 lakes that have already generated GLOFs, and found that our results agree well with previous studies. For the first time in GLOF risk assessment, we employed sensitivity analyses to test the strength of our model results and assumptions, and to identify lakes that are sensitive to the criteria and risk thresholds used. A key benefit of the MCDA method is that sensitivity analyses are readily undertaken. Overall, these sensitivity analyses lend support to our model, although we suggest that further work is required to determine the relative importance of assessment criteria, and the thresholds that determine the level of risk for each criterion. As a case study, the tested method was then applied to 25

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potentially dangerous lakes in the Bolivian Andes, where GLOF risk is poorly understood; 3 lakes are found to pose 'medium' or 'high' risk, and require further detailed investigation.

1. Introduction

Glaciers in most parts of the world are receding and thinning in response to climate change (Zemp et al., 2015). Glacier recession into rock basins and behind moraines leads to the ponding of meltwater as proglacial lakes (e.g. Carrivick and Tweed, 2013; Cook and Quincey, 2015), and glacier thinning results in the development of supraglacial lakes, particularly on debris-covered glaciers (e.g. Benn et al., 2001; Thompson et al., 2012; Mertes et al., 2016). Consequently, there has been a general trend of increasing glacial lake number and size in many regions in recent times (e.g. Carrivick and Tweed, 2013). Glacial lake outburst floods (GLOFs) may occur where the impounding dam (ice, rock, moraine, or combination thereof) is breached or overtopped. Thousands of people have lost their lives to such events in the last few decades, mostly during the 1941 GLOF at Huaraz, Peru, and the 2013 Kedernath event, India (Richardson and Reynolds, 2000; Allen et al., 2015; Carrivick and Tweed, 2016). Given the risk posed to downstream communities, industry and infrastructure in deglaciating mountain ranges worldwide, there has been an intensification of research interest in GLOFs (Emmer and Vilímek, 2013), with many such studies seeking to estimate GLOF hazard or risk for individual lakes or in specific regions including North America (Clague and Evans, 2000; O'Connor et al., 2001; McKillop and Clague, 2007a, 2007b), South America (Emmer and Vilímek, 2013; Anacona et al., 2015; Cook et al., 2016; Emmer et al., 2016a; Frey et al., 2016), the European Alps (Huggel et al., 2004; Frey et al., 2010), central Asia (Bolch et al., 2008; Mergili and Schneider, 2011; Petrov et al., 2017), and the Himalayas (Wang et al., 2008; Ives et al., 2010; ICIMOD, 2011; Ashraf et al., 2012; Worni et al., 2013; Watson et al., 2015; Aggarwal et al., 2016; Rounce et al., 2016).

Existing GLOF hazard and risk assessments are usually designed for specific purposes (e.g. estimating hazard, susceptibility or risk), specific regions or sites, specific lake contexts (e.g. ice-dammed or moraine-dammed), or require certain types, amounts, or detail of input data, or some combination of the above. These tailored risk assessments are very valuable for their stated purpose, but because of their specific conditions, the extent to which these techniques can be applied to other areas or lake types is uncertain, which itself often necessitates the development of additional region-, site-, or context-specific risk or hazard assessments. In addition, there is often a lack of transparency about why specific criteria are chosen, indicating that hazard and risk assessments are sometimes subjective in their design (McKillop and Clague, 2007a, 2007b).

Nonetheless, some hazard and risk assessments, although developed initially for, and applied to, specific regions, have been designed in such a way that they can be applied elsewhere. Most are designed for moraine-dammed lakes. Notable examples include those of McKillop and Clague (2007b), Mergili and Schneider (2011), and Rounce et al. (2016). McKillop and Clague (2007b) developed an objective method for assessing outburst flood hazard from moraine-dammed lakes in British Columbia, which uses remote sensing methods. Nevertheless, as a hazard assessment it does not evaluate impacts, exposure, vulnerability or risk, and cannot be applied to bedrock- or ice-dammed lakes, which may also exist within the same region. Mergili and Schneider (2011) developed a GLOF hazard assessment based on remote sensing data that could be applied to any lake type, but their method does not consider impacts on humans or infrastructure. Rounce et al. (2016) presented an objective and repeatable method for GLOF hazard and impact assessment, but this was based on moraine-dammed lakes only.

The purpose of this study is to present a decision-aid procedure that can be employed to identify those lakes within any given region that represent the greatest GLOF threat to downstream communities and infrastructure. This procedure, which employs Multi-Criteria Decision Analysis (MCDA), is not specific to any one glacial lake type, which is desirable because it permits the relative threat of impact to be assessed simultaneously for moraine-, ice-, and bedrock-dammed lakes, all of which may exist within the region of interest, as well as composite forms. This enables the generation of standardised results and the determination of appropriate action across the spectrum of glacial lake types. As with some existing GLOF hazard and risk assessments, our MCDA method also uses freely and widely available data and software, without the need for detailed site knowledge, nor field-derived data. As we explain in Section 2, MCDA involves the application of strict rules about the use of exhaustive, non-redundant and consistent criteria through the formulation of a 'Description Problem', meaning that subjective selection of criteria is minimised. Another key advantage of the software used for MCDA is that sensitivity analyses are readily undertaken such that the robustness of the model and its assumptions can be evaluated. To our knowledge, sensitivity analysis has not been undertaken for any previous GLOF hazard or risk assessment. We envisage that our method is most appropriately applied to regions where a variety of glacial lake types exist so that their relative threat can be assessed simultaneously, where field data are sparse or non-existent, and as a preliminary assessment of the threat posed by GLOFs to people or infrastructure. Once the most dangerous lakes are identified, future detailed field campaigns, flood modelling, and risk mitigation strategies can be employed. An example of where such an approach would be of value is the Bolivian Andes (Cook et al., 2016) where GLOFs from a range of glacier lake types pose a possible threat to downstream areas, but field data are sparse, and collection of such data would be complicated by poor accessibility to sites.

Our objectives are: (1) to define a set of robust (i.e. exhaustive, non-redundant, consistent) susceptibility and potential downstream impact criteria that will be used to define GLOF risk; (2) to use these criteria to assess GLOF risk for 22 lakes around the world and compare our results with those of previous GLOF risk and hazard studies; (3) to undertake sensitivity testing of the MCDA model in order to evaluate the robustness of the method; and (4) apply our model to assess the risk posed by 25 lakes in the Bolivian Andes, which represents a case study of how our model could be used.

A range of terms have been used interchangeably and inconsistently in GLOF 'hazard' and 'risk' studies. These include 'hazard', 'risk', 'susceptibility', 'danger', 'threat', 'impact', 'exposure', and 'vulnerability'. Further, definitions of 'hazard' and 'risk' can vary significantly between different branches of risk management science. In the natural sciences, for example, 'risk' is often taken to be the product of hazard and vulnerability, and sometimes exposure also (e.g. IPCC, 2014); however, international guidelines for the broad and varied fields of risk management science do not necessarily subscribe to such algorithms (see ISO 31000:2009 and The Society for Risk Analysis glossary). For the purposes of our MCDA model, we consider the physical properties of the glacial lakes, and the characteristics of the surrounding landscape and environmental context that may promote or trigger a GLOF event, to be the 'susceptibility' factors that drive the 'hazard' (i.e. a GLOF). The criteria associated with effects on downstream communities in our MCDA model are termed 'potential downstream impacts'. Whilst the product of susceptibility and downstream impacts do not equal risk according to the aforementioned algorithm sometimes used in natural risk science, we use the term 'risk' here to refer to consideration for, and combination of, impacts and susceptibility. This is a convenient short-hand term, and remains consistent with the more general definitions of risk laid out in ISO 31000:2009.

2. Methodology

2.1. Background to setting an MCDA problem

MCDA is a sub-field of operations research and management science that focuses on the development of decision support tools and methodologies to resolve complex decision problems. It has been applied previously across a number of environmental and natural disaster related problems including floods, landslides, avalanches and water management (e.g. Merad et al., 2004; Marinoni, 2005; Lin, 2008; Akgun and Türk, 2010; Behzadian et al., 2010; Huang et al., 2011; Stecchi et al., 2012; Tacnet et al., 2014; Brito and Evers, 2016). It is notable that MCDA has not yet been applied to assess GLOF risk. Specifically, MCDA can be applied across a region that contains numerous glacial lake types in order to determine which lakes, if any, should be selected for more detailed analysis, monitoring, or remediation work. The use of freely available tools and datasets, and the ease and relatively rapid deployment of our MCDA approach makes this an effective and efficient technique in areas where detailed knowledge and field data are limited.

In MCDA, a typical problem would be the task of defining the risk between a finite set of decision alternatives (e.g. determining, from a population of glacial lakes, which lakes could generate dangerous GLOFs), each of which is characterised by a set of criteria that must be considered simultaneously (Ishizaka et al., 2012). In this case, we consider all alternatives (i.e. glacial lakes) in a region that are characterised by a set of criteria (e.g. regional seismic activity, dam stability, potential loss of life). In practice, problems faced by experts or decision-makers in natural hazard or risk management can be a combination of four basic problems (Roy, 1996):

a) Description Problem: This is used in order to provide a number of alternatives (e.g. dangerous glacial lakes) and a suitable set of criteria, without making any recommendation about the final decision (e.g. which lakes represent the highest risk). Criteria that will be used in the MCDA are chosen according to past literature and a set of guidelines that will be discussed in Section 2.2.
b) Sorting Problem: Alternatives (i.e. glacial lakes) are sorted into ordered, pre-defined categories. A sorting problem can also be used for screening in order to reduce the number of alternatives that are to be considered. For example, all lakes within the study area are sorted according to GLOF risk for downstream communities with categories such as "high risk", "medium risk", and "low risk".
c) Ranking Problem: Alternatives (i.e. glacial lakes) are classified from highest to lowest risk; equal ranks are possible. For example, all lakes in the study area are ascribed a numerical value from 1 to *n* depending on their level of GLOF risk to downstream communities, but some lakes may have risk equal to one another and so share the same rank value.
d) Choice Problem: This is used to select a single alternative or to reduce the group of alternatives to a subset of equivalent or incomparable alternatives. An example would be to select a single lake with the highest risk to downstream population; all other lakes would be excluded from further analysis.

Previous studies of GLOF hazard or risk have used a wide range of criteria, which reflects variability in the type and amount of data available, and the specific objectives of the assessment procedure (e.g. evaluating hazard or risk, across a region or individual site, and for different lake contexts). Hence, the first task of this study can be framed as a Description Problem, where the main (sub-) criteria that determine the risk of a lake outburst to downstream communities must be defined, with consideration for the range of assessment criteria used in previous studies.

Next, these criteria will be used to frame a Sorting Problem whereby lakes will be classed according to high, medium or low risk, which can be used to narrow future research or mitigation focus onto the most dangerous lakes. The Sorting Problem has been chosen in this study instead of ranking or choice problems because it offers the possibility of evaluating a large set of lakes, but also a single lake. The Ranking Problem suffers from the shortcoming that at least two lakes need to be studied in order for the assessment to take place; the Choice Problem will only define the highest risk lake. Our MCDA approach for GLOF risk is designed to be intuitive, to use freely available datasets, and be applicable to any glacial lake irrespective of dam type or region of the world.

2.2. The description problem: determining the criteria that define GLOF risk

Previous reviews of GLOF hazard and risk assessments have highlighted how a wide variety of criteria have been used in different studies to determine GLOF risk (e.g. Emmer and Vilímek, 2013; Rounce et al., 2016). Others have gone further, suggesting that many assessments are made through subjective and non-transparent selection of criteria (McKillop and Clague, 2007b). MCDA alleviates this issue to some extent by developing a "coherent set" of criteria. In order to achieve this, the following properties need to be fulfilled (Roy, 1996):

- Exhaustiveness: all possible criteria are taken into account, and nothing important is left out. For example, a criterion, such as rockfall/landslide susceptibility, is actually a composite of multiple criteria (e.g. slope steepness, seismic activity) (Fig. 1). Hence, such composite criteria should be split into separate criteria to avoid bias in the final estimation of risk. This has not always been done in previous studies (e.g. Costa and Schuster, 1988; Huggel et al., 2004; Bolch et al., 2008; Emmer and Vilímek, 2013; Aggarwal et al., 2016; Rounce et al., 2016). Table 1 shows the exhaustive list of 79 criteria from which 13 have been selected.
- Non-redundancy: no double counting; all the unnecessary criteria must be removed. Some assessments effectively examine the same criteria twice, which biases the risk assessment. For example, glacier snout steepness and presence of a crevassed glacier snout above the lake both lead to a greater probability of ice calving into the lake, which raises the risk of a GLOF (e.g. Grabs and Hanisch, 1992; Zapata, 2002; Wang et al., 2011). However, these two criteria are strongly related - steeper glaciers will generally flow faster, which causes more crevassing, and greater ice calving potential. Therefore, only one representative criterion should be evaluated.
- Consistency: the criteria must not hide any preferences. A criterion can only have a positive or negative effect on the choice of alternative (e.g. lake), but can never have both effects simultaneously. For example, glacier shrinkage can have a two-way effect. For moraine-dammed lakes, glacier shrinkage will reduce the risk of calving or ice/snow avalanches into the lake, and hence reduce the risk of a GLOF produced by a displacement wave. But, for ice-dammed lakes, glacier shrinkage can increase the risk of GLOFs because the ice dam disintegrates or becomes more susceptible to flotation or tunnelling by meltwater (e.g. Tweed and Russell, 1999). Hence, criteria need to be selected such that their effects operate in the same direction. This rule has not been used yet in previous assessments since these studies do not usually perform an evaluation across multiple dam types. Nevertheless, this is important in our study as the MCDA method we are using is applicable across all dam types.

In an attempt to meet these characteristics, we compiled a list of all the criteria that have previously been used in GLOF risk and hazard

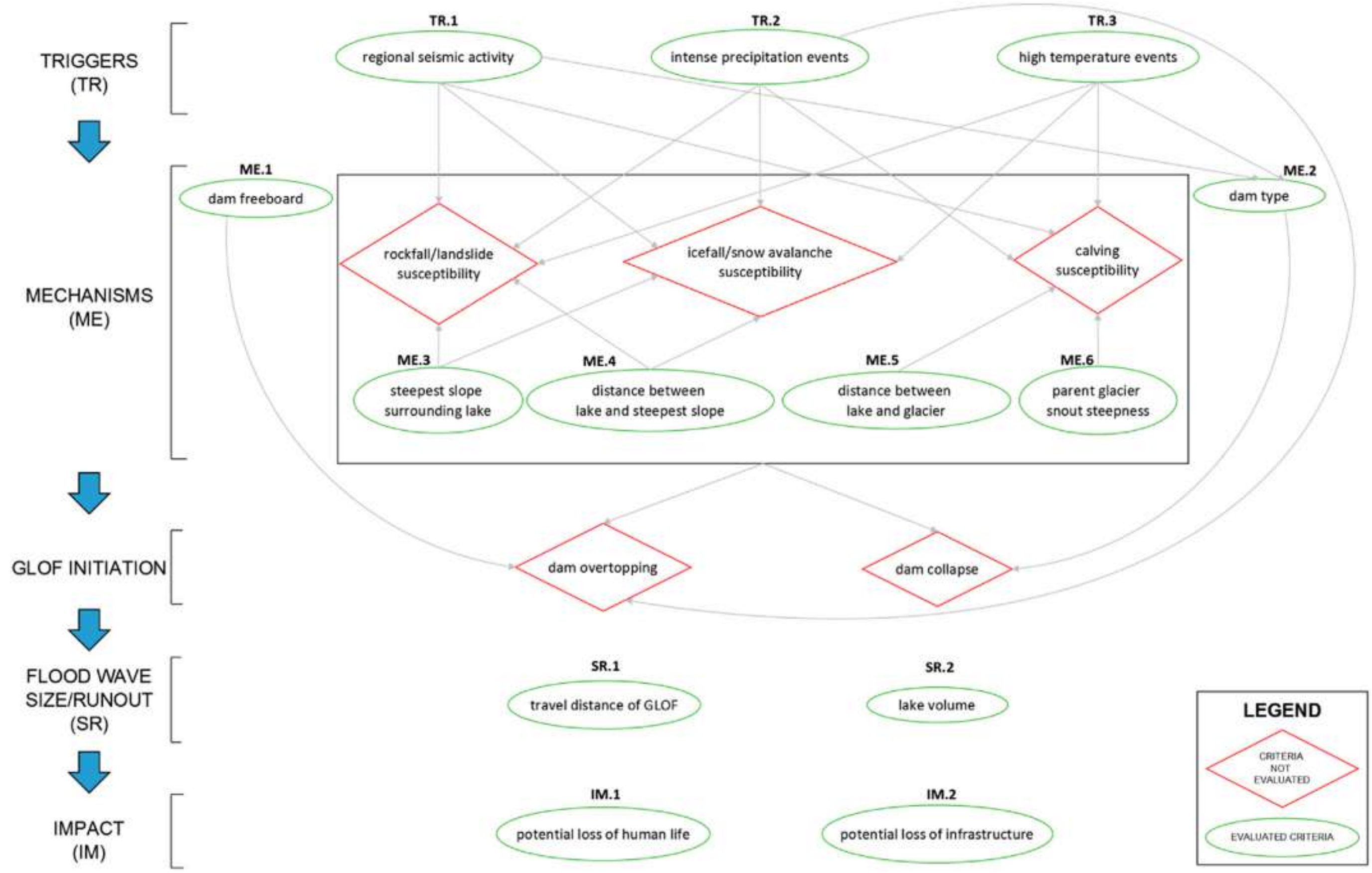

Fig. 1. Flow diagram of the GLOF risk assessment procedure. Supplementary information about the final set of criteria can be found in Appendix A.

assessments (Table 1). Several studies (e.g. Huggel et al., 2004; Bolch et al., 2008; Mergili and Schneider, 2011; Emmer and Vilímek, 2013; Worni et al., 2013; Rounce et al., 2016) have also compiled and/or reviewed a number of these criteria. However, in many studies, the final selection of criteria that are used to make the risk assessment is often made (1) seemingly on a subjective or non-transparent basis, or (2) based on the frequency of use in previous studies (e.g. a tally chart). To some extent, this reflects specific local or regional needs or issues, or specific data requirements or availability. But for areas where there are limited data or knowledge, the MCDA guidelines outlined above serve to reduce user bias in the selection of criteria by first considering all available criteria, and streamlining them to avoid issues of non-exhaustiveness, redundancy, and non-consistency. Table 1 was generated from 30 studies and lists 79 factors in total. Through consideration of their exhaustiveness, non-redundancy, and consistency, we identified 13 criteria that can be used for GLOF risk analysis of any lake, in any part of the world, from freely available data or satellite imagery. Hence, several criteria were rejected because they were either non-exhaustive, redundant, or non-consistent, would have necessitated fieldwork, or that were specific to a region or a particular lake type. Fig. 1 illustrates how, from the 13 criteria, lakes are assessed according to their GLOF risk. Details about each criterion are provided in the Supplementary data - Appendix A. If local data exist for any of these criteria, their use is strongly encouraged.

2.3. The sorting problem: past GLOF events and potentially dangerous lakes

Following the identification of appropriate selection criteria from the Description Problem stage, all lakes within a region can be judged according to those criteria in order to determine which lakes, if any, represent a GLOF risk to downstream communities. This can be achieved remotely (i.e. without the need for fieldwork), and without cost, as we demonstrate below. Our approach can be applied to a single lake or to a complete lake inventory within a region. It would be particularly useful in identifying sites for further detailed field studies, outburst flood modelling, or monitoring. In this study, we apply our method on a number of lakes that had been identified in previous studies as representing a threat to downstream communities. Fig. 2 illustrates the steps that need to be followed for the method to be applied in a chosen region. For the trigger criteria (TR.1, 2, 3), the user will need to open the indicated databases (Global seismic hazard map, BIOCLIM variables 4 and 5) in a GIS in order to evaluate the lakes. For all other criteria, Google Earth Pro is sufficient for evaluation. Additional information about criteria evaluation can be found in Table 2 and Appendix A.

2.3.1. Choice of lakes for testing

Our MCDA method was applied to 22 glacial lakes from a number of locations around the world in order to test and evaluate the performance of the model globally. We chose a mix of lakes that have been the subject of previous GLOF hazard or risk studies (where MCDA has not been used), as well as lakes that are known to have generated GLOFs. The 6 GLOF-generating lakes were selected based on two important characteristics:

- There is existing literature describing the downstream impact of the GLOF;
- There is free, high-resolution satellite imagery (e.g. integrated into Google Earth) before the GLOF event, which makes the pre-GLOF lake risk assessment possible.

Of these lakes, one is located in Norway (Flatbreen lake - Breien et al., 2008), one in Bolivia (Keara lake - Hoffmann and Wegenmann, 2013), one in Peru (Lake 513 - Carey et al., 2012; Klimeš et al., 2014;

Table 1
Review of criteria assessed in previous studies. Top section outlines the process followed to accept or reject a criterion. Middle section shows the results. Bottom section illustrates the literature used. The accepted criteria in the middle section are illustrated in Fig. 1.

Accepted/rejected criterion	Reason	Indication
Rejected criterion	Dam, region or scenario specific	A
	Field assessment required	B
	Non-exhaustive	C
	Redundant	D (with which criterion)
	Non-consistent	E
Accepted criterion	No issue	✓

ID	Criterion	Source	Accepted/rejected criterion
TR.1	Regional seismic activity	4,15,18,28	✓
TR.2	Precipitation seasonality (intense precipitation events)	8,13	✓
TR.3	Temperature seasonality (high temperature events)	8,13	✓
ME.1	Dam freeboard	2,3,4,5,15,17,18,21,30	✓
ME.2	Dam type	4,8,12,15,17,29,30	✓
ME.3	Steepest slope surrounding lake	6,11,14	✓
ME.4	Distance between lake and steepest slope	9,26	✓
ME.5	Distance between lake and glacier	2,4,5,14,16,24,26	✓
ME.6	Parent glacier snout steepness	2,4,11,13,16	✓
SR.1	Travel distance of GLOF	8,17,23,28	✓
SR.2	Lake volume	4,7,21,26	✓
IM.1	Potential loss of human life	28	✓
IM.2	Potential loss of infrastructure	28	✓
1	Hydrometeorological situation	18	C
2	Mass movement into lake/potential for lake impact	1,8,11,18,21,24,30	C
3	Snow avalanche/icefall susceptibility	4,7,14,15,17,21,28	C
4	Rockfall/landslide susceptibility	2,3,4,14,15,17,21,28	C
5	Slope of lateral moraines and possibility of its fall into the lake	2,19	C
6	Interconnected lakes/unstable lake upstream	6,18,24,28,30	C
7	Calving susceptibility	15	C
8	Slope between lake and glacier snout	16	D (with ME.6)
9	Crevassed glacier snout above lake	2,3,4	D (with ME.6)
10	Stagnant ice at the glacier terminus	14	B
11	Area of the mother glacier	13,16	E
12	Glacier advance	2	E
13	Glacier shrinkage	14	E
14	Reaction of the glacier to climate change	11	E
15	Contact with glacier	6,26	D (with ME.5)
16	Maximum area of inundation	10	D (with SR.1)
17	Amount of loose material/maximum debris flow volume	6	B
18	Lake area and/or size	4,10,14,19,24,26	D (with SR.2)
19	Breach volume	6	B
20	Lake area change	11,14,15,28	D (with SR.2)
21	Lake depth	4,21,26	D (with SR.2)
22	Distant flank steepness of the dam	1,4,13,15,16	A,B
23	Width and/or height ratio of dam	3,4,8,10,12,13	B
24	Top width of dam	13,19	A, B
25	Steepness of moraine	2	A
26	Piping/seepage through moraine	2,3,4,7,12,15,19	A,B
27	Buried ice in moraine	1,2,7,8,10,11,13	A,B
28	Main rock type of moraine	10	A,B
29	Moraine slope stabilised by vegetation	1	A
30	Supra/englacial drainage	7,30	A,B
31	Piping gradient	19	A,B
32	Lake perimeter	19	A
33	Lake width	19	A
34	Dam height	19	A
35	Maximum slope of distal face of the dam	19	A,B
36	Mean slope between lake and glacier	19	D (with ME.6)
37	Mean slope of lake surrounding	19	D (with ME.3)
38	Hydrostatic pressure	28	B
39	Lake elevation	20	D (with TR.2)
40	Nonglacial watershed component	20	D (with TR.2)
41	Mean stream size	20	D (with TR.2)
42	Drainage density	20	D (with TR.2)
43	Mean slope	20	D (with TR.2)
44	Population density	22	B
45	Livestock density	22	B
46	Cultivated area	22	B
47	Density of road network	22	B
48	Density of agricultural economy	22	B
49	Proportion of rural population	22	B
50	Percentage of small livestock	22	B
51	Road level	22	B
52	Building level	22	B
53	Regional GDP	22	B
54	Financial revenue share of GDP	22	B
55	Density of fixed assets investment	22	B
56	Female population	25	B
57	Population < 6 years of age	25	B
58	Population > 60 years of age	25	B
59	Literacy rate	25	B
60	Unemployment	25	B
61	Employment in farming	25	B
62	Disabled population	25	B
63	Home renters	25	B
64	Derelict houses	25	B
65	Water availability	25	B
66	Medical facilities	25	B
67	Education facilities	25	B
68	Banking services	25	B
69	Access to radio	25	B
70	Access to TV	25	B
71	Access to internet	25	B
72	Access to mobile	25	B
73	Access to vehicle	25	B
74	Economical vulnerability	27	B
75	Social vulnerability	27	B
76	Institutional vulnerability	27	B
77	Building materials	27	B
78	Geology and type of soil	27	B
79	Land use laws	27	B

1: Costa and Schuster (1988); 2: Grabs and Hanisch (1992); 3: Clague and Evans (2000); 4: Zapata (2002); 5: O'Connor et al. (2001); 6: Huggel et al. (2002); 7: Reynolds (2003); 8: Huggel et al. (2004); 9: Rickenmann (1999, 2005); 10: McKillop and Clague (2007a, 2007b); 11: Bolch et al. (2008); 12: Hegglin and Huggel (2008); 13: Wang et al. (2008); 14: Bolch et al. (2011); 15: Mergili and Schneider (2011); 16: Wang et al. (2011); 17: Worni et al. (2013); 18: Emmer and Vilímek (2013); 19: Emmer and Vilímek (2014); 20: Allen et al. (2015); 21: Vilímek et al. (2015); 22: Wang et al. (2015); 23: Watson et al. (2015); 24: Allen et al. (2016); 25: Aggarwal et al. (2016); 26: Cook et al. (2016); 27: Frey et al. (2016); 28: Rounce et al. (2016); 29: Carrivick and Tweed (2016); 30: Petrov et al. (2017).

Vilímek et al., 2015), one in Nepal (Halji lake - Kropáček et al., 2015), one in Pakistan (Passu lake - Ashraf et al., 2012), and one in India (Chorabari lake - Das et al., 2015). Hence, a wide range of locations are represented.

The remaining 16 lakes have not yet burst but are considered potentially dangerous by other GLOF hazard/risk assessments that have made use of multiple criteria: one is located in Peru (Hanpi k'ocha - Frey et al.,

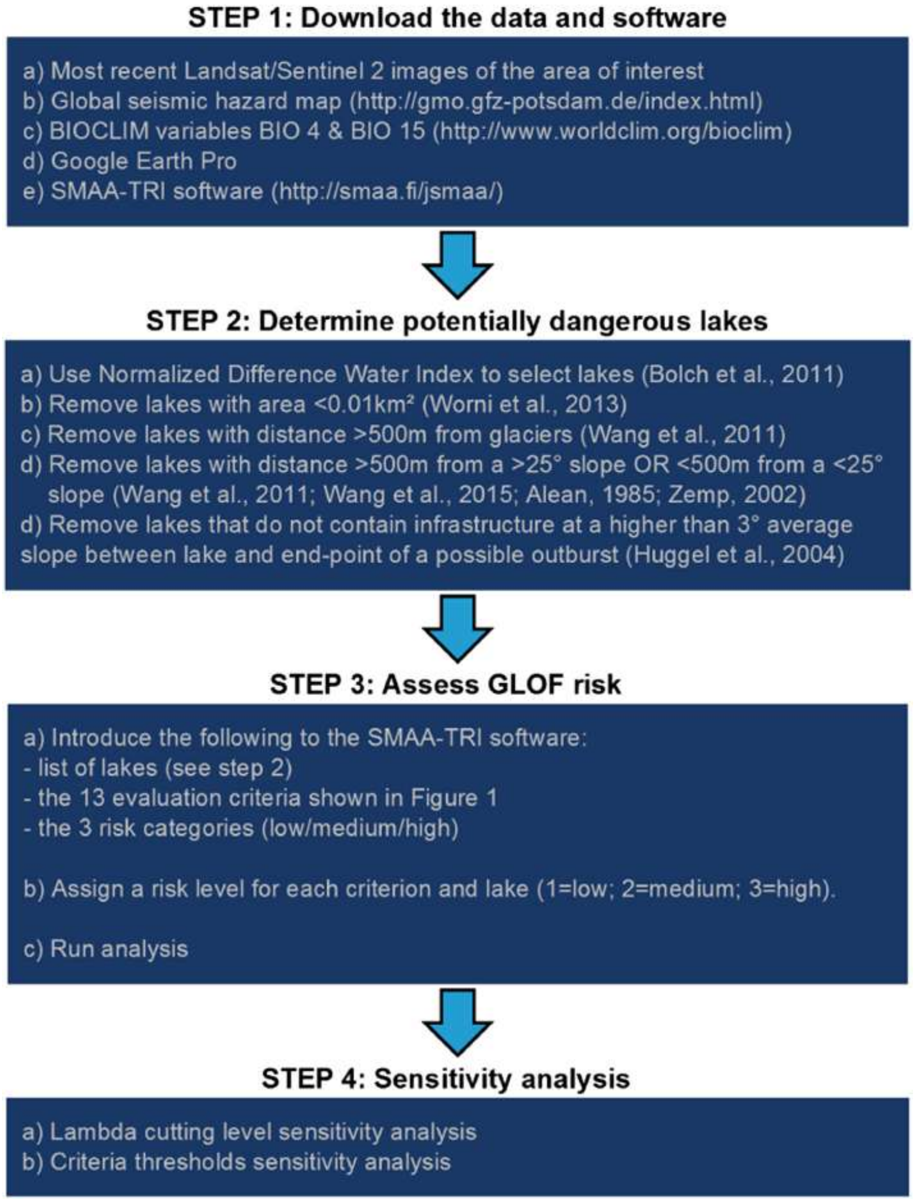

Fig. 2. Five-step flow diagram for the Multi-Criteria Decision Analysis (MCDA) method. Step 1: the user downloads all data and software needed for the evaluation; Step 2: the proglacial lake dataset to be analysed is extracted; Step 3: introducing the parameters to the software and computation of the result; Step 4: Sensitivity Analysis.

2016), five are located in India (Gopang Gath, Spong Tongpo, Schako Tsho - Worni et al., 2013; Chollamo, Lake 0071 - Aggarwal et al., 2017), eight in Nepal (Imja Tsho, Tsho Rolpa, Thulagi Tsho, Dig Tsho, Lower Barung Tsho, Ludming Tsho, Chamlang South Tsho, Chamlang North Tsho - Rounce et al., 2016) and two in New Zealand (Maud lake, Godley lake - Allen et al., 2009). Values for each criterion were assigned for the lakes (see also Supplementary data - Appendix B, Tables B.1 and B.2) and the analysis was run using the SMAA-TRI software (see Section 2.3.2).

2.3.2. SMAA-TRI software

A range of different software packages and methods have been developed for resolving complex sorting problems in MCDA: e.g. FlowSort (Nemery and Lamboray, 2008), ELECTRE-Tri (Mousseau et al., 2000), AHPSort (Ishizaka et al., 2012). ELECTRE-TRI has been used by Merad et al. (2004) to identify zones subject to mining-induced risk; Stecchi et al. (2012) used the same software to assess vulnerability due to ground deformation phenomena. In this study, we use SMAA-TRI (Stochastic Multi-criteria Acceptability Analysis, http://smaa.fi/), a free-to-download upgraded version of ELECTRE-TRI (Tervonen, 2012). SMAA methods allow the tackling of problems with imprecise information, similar to the criteria used in GLOF multi-criteria assessments. Imprecise information means that the value is present but not always with the required precision (Tervonen, 2012; Malczewski and Rinner, 2015). A review of all the ELECTRE method packages can be found in Figueira et al. (2013).

2.3.3. Setting risk thresholds and codes for evaluating individual criteria

Table 2 presents the threshold values that we have used to define the risk classes for each criterion in the sorting method (see also Supplementary data - Appendix A). The software allows the user to set the evaluation codes. For this model, three codes where set: 1 (low risk), 2 (medium risk) and 3 (high risk). These values are used to assign each criterion to a predefined risk class, from which a total risk score can be calculated for each lake.

The relative importance of each criterion can differ, and there are numerous methods for determining the relative weights of individual criteria (Saaty, 1977; Chen et al., 2001; Figueira and Roy, 2002). In a

Table 2
Criteria units, evaluation methods, main risk thresholds and sensitivity analysis thresholds. Details on criteria threshold determination can be found in Appendix A.

ID	Criteria	Unit	Low risk	Medium risk	High risk	Evaluation tool	Sensitivity analysis	Threshold variations for sensitivity analysis
Triggers								
TR.1	Regional seismic activity	pga in m/s^2	<0.5	0.5–3.9	>3.9	USGS/Global Seismic Hazard Map-GSHAP	✓	<0.5, 0.5–1.9, >1.9
TR.2	Intense precipitation events	Precipitation seasonality in %	<50	50–100	>100	Bioclim 15 - precipitation seasonality	✓	<25, 25–75, >75
TR.3	High temperature events	Temperature seasonality in %	<50	50–100	>100	Bioclim 4 - temperature seasonality	✓	<25, 25–75, >75
Mechanisms								
ME.1	Dam freeboard	m	>15	15–5	<5	Google Earth/Bing Maps	Not enough detail	
ME.2	Dam type	Type	Bedrock	Moraine	Ice	Google Earth/Bing Maps	Qualitative	
ME.3	Steepest slope surrounding lake	Degrees	<30	30–45	>45	Google Earth/Bing Maps	✓	<20, 20–30, >30
ME.4	Distance between lake and steepest slope	m	500–250	250–10	10-contact	Google Earth/Bing Maps	✓	500–250, 250–50, <50
ME.5	Distance between lake and glacier	m	500–250	250–10	10-contact	Google Earth/Bing Maps	✓	500–250, 250–50, <50
ME.6	Parent glacier snout steepness	Degrees	<15	15–25	>25	Google Earth/Bing Maps	Not enough detail	
Flood wave size/runout								
SR.1	Travel distance of GLOF	Degrees	3–7	7–11	>11	Google Earth/Bing Maps	✓	3–6, 6–9, >9
SR.2	Lake volume	m3 $*$ 10^6	<1 $*$ 10^6	1 $*$ 10^6–10 $*$ 10^6	>10 $*$ 10^6	Google Earth/Bing Maps for area + equation	✓	<0.1 $*$ 10^6, 0.1 $*$ 10^6–1 $*$ 10^6, >1 $*$ 10^6 (1 order of magnitude lower threshold)
Impact								
IM.1	Potential loss of human life	Individuals	<10	10–1000	>1000	Google Earth/Bing Maps/web info	✓	<10, 10–100, >100
IM.2	Potential loss of infrastructure	Infrastructure	Agricultural fields, roads etc.	Houses, bridges etc.	Hydropower, mining camp etc.	Google Earth/Bing Maps/web info	Qualitative	

natural hazard context, weights are typically determined subjectively by the hazard/risk experts or based on statistical methods (such as regression and principal component analysis) (Chen et al., 2001). However, since there is insufficient empirical evidence by which to determine the relative importance of each criterion in GLOF risk or hazard assessments, the decision was made here not to assign any weights. Nonetheless, this could be undertaken in future studies if understanding of GLOF controlling factors were to develop sufficiently.

2.3.4. Sensitivity analysis

In MCDA, sensitivity analysis serves to determine how much the uncertainty of the results of a model are influenced by the uncertainty of its input criteria (Saltelli et al., 1999). Sensitivity analysis can be performed using different methods. The robustness of the model can be assessed by analysing its sensitivity to the alteration of parameter λ (lambda), the criteria thresholds, and their assigned weights (Roy, 1993). The criteria used in this study do not hold weights, so the two sensitivity analyses to be undertaken are (1) the alteration of the λ-cutting level, and (2) the variation of the criteria thresholds.

2.3.4.1. Lambda cutting level. The λ-cutting level indicates how many of the criteria have to be fulfilled in order to assign an alternative (i.e. a lake) to a specific risk category, and it can be altered within the software. The cutting level must be set to between 0.5 and 1.0 (Damart et al., 2007); a cutting level of 0.5 means that at least 50% (i.e. 7 criteria) of the 13 criteria would need to be evaluated as 'high risk' in order to assign a lake in the high risk category overall. Several studies have discussed the assignment of an appropriate cutting level, and it is generally accepted that it should be greater than the highest weight (Figueira and Roy, 2002; Merad et al., 2004; Brito et al., 2010; Tervonen, 2012; Sánchez-Lozano et al., 2014). Since no weights were assigned in this study, we present a series of scenarios in Table 4 where the cutting level is set to 0.65, 0.7, 0.75, 0.8, and 0.85. The objective here is to assess whether any lakes change risk category as the cutting level is changed from its least conservative level (0.65) to its most conservative level (0.85). The percentages in each risk class show the level of confidence with which the software assigns each lake to a class. The higher the percentage, the higher the probability of a lake belonging to that specific risk class. If percentages between two risk classes are equal, then the GLOF risk for that lake will be classified automatically in the higher risk class, since risk analysis is generally a conservative exercise (Merad et al., 2004).

2.3.4.2. Criteria thresholds. The second sensitivity analysis examines the extent to which risk classifications will change if the threshold values used for each criterion are altered (both the original thresholds and the revised thresholds used for the sensitivity analysis can be found in Table 2). For this analysis, the λ-cutting level was kept at 0.65, and thresholds were changed for 9 of the 13 criteria; thresholds for the 4 remaining criteria (ME.1, 2, 6 and IM.2) could not be altered either because the resolution of the remote sensing data was insufficient to allow any meaningful threshold changes to be made, or because of the qualitative nature of the threshold limits. We took a conservative approach whereby the thresholds for the highest levels of risk for each criterion were relaxed in order to determine whether any lakes then fell into the high risk category overall.

3. Results

3.1. Assessing GLOF risk: an application to past and potential future events

Table 3 shows the lakes considered in this study alongside the level of risk posed to downstream communities, which was determined using our MCDA approach. The results show that 11 lakes pose a high risk to downstream communities, six lakes are ranked as medium risk, and five as low-risk. Since susceptibility and downstream impacts are both evaluated in the same computational step, the outcome (risk classes) shows the combination of GLOF impact severity and potential outburst susceptibility. A lake can become classified as high risk either due to high outburst susceptibility parameters, such as elevated regional seismic activity and steep slopes surrounding the lake, or because of severe potential impacts, such as a large population downstream, or the presence of high-value infrastructure.

3.2. Lambda cutting level sensitivity analysis

The results of this first sensitivity analysis are shown in Table 4. All lakes that are already classified as high risk when the cutting level is at 0.65 will not change class with an increase in the cutting level. This is because as the cutting level is increased (0.70, 0.75, etc.), a lower proportion of criteria graded as 'high risk' (30%, 25%, etc.) are needed in order to classify a lake as 'high risk' overall. Lakes classified as medium or low-risk when the cutting level is 0.65 may be reclassified into a higher risk class as the cutting level is increased. Taking the example of the five low-risk lakes, the number of low-risk criteria is sufficiently important to maintain the lakes as low risk no matter what cutting level is used. Two of the lakes classed as medium risk with a cutting level of 0.65 (Keara Lake and Hanpi k'ocha) move into high-risk categories when the cutting level is increased by one increment to 0.7, and a further three when the cutting level is increased to 0.75. Gopang Gath is the only lake that maintains its medium-risk score until the penultimate computational step ($\lambda = 0.80$), after which it shifts to high risk ($\lambda = 0.85$).

Table 4
Sensitivity analysis based on alteration of the lambda cutting level. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific risk class. Low risk = Green, Medium risk = Orange, High risk = Red.

Dangerous lakes - literature	λ-cutting level				
	0.65	0.7	0.75	0.8	0.85
Maud Lake	0.97	0.98	0.97	0.93	0.86
Godley Lake	0.89	0.89	0.84	0.72	0.56
Chholamo	0.89	0.89	0.84	0.73	0.56
Lake 0071	0.58	0.72	0.82	0.87	0.84
Hanpi k'ocha	0.62	0.49	0.64	0.79	0.91
Gopang Gath	0.92	0.83	0.70	0.50	0.44
Spong Tongpo	0.70	0.53	0.38	0.56	0.73
Schako Tsho	0.78	0.88	0.94	0.98	1.00
Imja Tsho	0.78	0.88	0.95	0.98	1.00
Tsho Rolpa	0.97	0.99	1.00	1.00	1.00
Thulagi Tsho	1.00	1.00	1.00	1.00	1.00
Dig Tsho	0.99	1.00	1.00	1.00	1.00
Lower Barung Tsho	0.97	0.99	1.00	1.00	1.00
Ludming Tsho	0.92	0.96	0.99	1.00	1.00
Chamlang South Tsho	0.91	0.96	0.99	1.00	1.00
Chamlang North Tsho	0.91	0.96	0.99	1.00	1.00
Selected GLOF events	λ-cutting level				
	0.65	0.7	0.75	0.8	0.85
Flatbreen Lake - 2004	0.57	0.68	0.73	0.69	0.55
Passu Lake - 2007	0.65	0.49	0.64	0.79	0.90
Keara Lake - 2009	0.52	0.49	0.65	0.80	0.91
513 Lake - 2010	0.65	0.50	0.65	0.80	0.91
Halji Lake - 2011	0.79	0.88	0.95	0.98	1.00
Chorabari Lake - 2013	0.59	0.73	0.85	0.93	0.98

3.3. Criteria thresholds sensitivity analysis

The results of this second sensitivity analysis are shown in Table 5. Respectively, Rows A and B indicate the number of lakes that change

Table 3
Potentially dangerous lakes and selected GLOF events derived from previous studies. Risk level derived from the MCDA method. Decimal percentages (i.e. from 0.5 to 1) indicate the level of confidence that a lake belongs to the specific risk class. Low risk = Green, Medium risk = Orange, High risk = Red.

Dangerous lakes - literature	Country	Reference	Coordinates in UTM			Risk Level
Maud Lake	New Zealand	Allen et al., 2009	59 G	459482	5185818	0.97
Godley Lake	New Zealand	Allen et al., 2009	59 G	461555	5188206	0.89
Chholamo	India	Aggarwal et al., 2017	45 R	672675	3099360	0.89
Lake 0071	India	Aggarwal et al., 2017	45 R	676212	3084379	0.58
Hanpi k'ocha	Peru	Frey et al., 2016	18 L	743739	8534059	0.62
Gopang Gath	India	Worni et al., 2013	43 S	708269	3601049	0.92
Spong Tongpo	India	Worni et al., 2013	43 S	658545	3769166	0.70
Schako Tsho	India	Worni et al., 2013	45 R	658915	3095511	0.78
Imja Tsho	Nepal	Rounce et al., 2016	45 R	492610	3085944	0.78
Tsho Rolpa	Nepal	Rounce et al., 2016	45 R	448360	3082066	0.97
Thulagi Tsho	Nepal	Rounce et al., 2016	45 R	253755	3153985	1.00
Dig Tsho	Nepal	Rounce et al., 2016	45 R	459210	3083375	0.99
Lower Barung Tsho	Nepal	Rounce et al., 2016	45 R	509355	3074824	0.97
Ludming Tsho	Nepal	Rounce et al., 2016	45 R	461884	3072885	0.92
Chamlang South Tsho	Nepal	Rounce et al., 2016	45 R	495956	3069986	0.91
Chamlang North Tsho	Nepal	Rounce et al., 2016	45 R	495685	3073227	0.91
Selected GLOF events	Country	Reference	Coordinates in UTM			Risk Level
Flatbreen lake - 2004	Norway	Breien et al., 2008	32 V	382775	6817696	0.57
Passu lake - 2007	Pakistan	Ashraf et al., 2012	43 S	489281	4034749	0.65
Keara lake - 2009	Bolivia	Hoffmann and Wegenmann, 2013	19 L	481958	8377253	0.52
513 lake - 2010	Peru	Carey et al., 2012; Klimeš et al., 2014; Vilímek et al., 2015	18 L	219809	8980678	0.65
Halji lake - 2011	Nepal	Kropácek et al., 2015	44 R	545635	3348799	0.79
Chorabari lake - 2013	India	Das et al., 2015	44 R	314434	3403219	0.59

Table 5
Sensitivity analysis of individual criteria as compared to results before sensitivity analysis (as in Table 3). Decimal percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk = Orange, High risk = Red). We also indicate the number of lakes that change A) risk class or B) confidence level for each criterion threshold change, and the number of times a lake changes C) risk class or D) confidence level for each criterion threshold change.

Dangerous lakes - literature	Results before sensitivity (as in Table 3)	TR.1	TR.2	TR.3	ME.3	ME.4	ME.5	SR.1	SR.2	IM.1	C	D
Maud Lake	0.97	0.94	0.97	0.91	0.94	0.97	0.97	0.97	0.97	0.97	0	3
Godley Lake	0.89	0.81	0.89	0.77	0.81	0.80	0.89	0.89	0.89	0.89	0	4
Chholamo	0.89	0.81	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0	1
Lake 0071	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.65	0.58	0.58	1	0
Hanpi k'ocha	0.62	0.58	0.62	0.62	0.62	0.62	0.62	0.62	0.58	0.62	2	0
Gopang Gath	0.92	0.81	0.92	0.92	0.92	0.92	0.92	0.95	0.92	0.92	0	2
Spong Tongpo	0.70	0.53	0.70	0.52	0.70	0.62	0.70	0.70	0.52	0.70	0	4
Schako Tsho	0.78	0.91	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.91	0	2
Imja Tsho	0.78	0.92	0.92	0.92	0.78	0.92	0.92	0.92	0.92	0.92	0	0
Tsho Rolpa	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0	0
Thulagi Tsho	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0	0
Dig Tsho	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0	0
Lower Barung Tsho	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0	0
Ludming Tsho	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0	0
Chamlang South Tsho	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0	0
Chamlang North Tsho	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0	0
Selected GLOF events	Results before sensitivity (as in Table 3)	TR.1	TR.2	TR.3	ME.3	ME.4	ME.5	SR.1	SR.2	IM.1	C	D
Flatbreen Lake - 2004	0.77	0.77	0.77	0.77	0.54	0.77	0.77	0.77	0.57	0.77	0	2
Passu Lake - 2007	0.65	0.58	0.65	0.58	0.65	0.65	0.65	0.65	0.58	0.65	3	0
Keara Lake - 2009	0.52	0.58	0.52	0.52	0.52	0.52	0.52	0.59	0.61	0.52	2	1
513 Lake - 2010	0.65	0.58	0.65	0.65	0.58	0.65	0.65	0.59	0.58	0.58	5	0
Halji Lake - 2011	0.79	0.79	0.92	0.79	0.79	0.79	0.79	0.79	0.91	0.92	0	3
Chorabari Lake - 2013	0.59	0.79	0.59	0.59	0.79	0.59	0.59	0.59	0.59	0.59	0	2
A		4	0	1	1	0	0	3	3	1		
B		8	1	3	4	1	0	1	4	2		

risk class and change risk classification confidence level when each criterion threshold is modified. Several criteria lead to little or no change to the number of lakes that are re-classified when their thresholds are modified, and only minor changes in the percentage of confidence in each risk class. These are intense precipitation events (TR.2), distance between lake and steepest slope (ME.4), and distance between lake and glacier (ME.5). Altering thresholds for high temperature events (TR.3), GLOF travel distance (SR.1), potential loss of human life (IM.1), and steepest slope surrounding the lake (ME.3), lead to a shift of up to three lakes from low to medium and from medium to high risk, and a change of confidence levels for up to four lakes. Threshold alterations for lake volume (SR.2) and regional seismic activity (TR.1) resulted in the greatest shift in lake risk classification, with three and four lakes respectively changing from medium risk to high risk, as well as four and eight lakes changing confidence levels respectively for SR.2 and TR.1.

Columns C and D in Table 5 illustrate, respectively, the number of times each lake changes risk class and confidence level within a class when a criterion threshold is changed. In summary, Maud lake, Godley lake and Chholamo all remain as low-risk throughout the process, but Lake 0071 shifts once from low risk to medium risk. Hanpi k'ocha and Keara lake change from medium to high risk twice, Passu lake three times, and lake 513 five times. Hence, Passu lake and lake 513 appear to be particularly sensitive to certain individual criteria thresholds being changed. Confidence levels remain stable in most cases, with some exceptions; Chholamo and Keara lakes undergo a shift in class confidence level once, and Gopang Gath, Schako Tsho, Flatbreen Lake and Chorabari lake twice. Furthermore, the confidence level changes three times for Maud lake and Halji lake, and four times for Godley lake and Spong Tongpo. Overall, the model results remain robust when thresholds are changed, but some lakes are identified through sensitivity analysis as being particularly sensitive, and hence possibly worthy of careful attention in any risk management decisions or actions.

3.4. Application to a data-scarce region: the Bolivian Andes

Here, we apply the MCDA method to glacial lakes of the Bolivian Andes, which is a region where GLOF risk has not yet been studied in detail, and where there are a range of lake types, and very little information about the nature of the lakes or the environment within which they are situated. Cook et al. (2016) performed a rudimentary assessment of the GLOF threat posed by Bolivian glacial lakes; their work amounts to the completion of Steps 1 and 2 in Fig. 2. They identified 137 lakes in total; from these lakes, 25 had population downstream and therefore required further investigation. This list includes a mix of moraine-dammed and bedrock-dammed lakes, although an ice-dammed lake at Keara burst in 2009, and is featured in our earlier model results. To assess GLOF risk for these 25 lakes, the λ-cutting level is set at 0.65 and the criteria thresholds are kept at their initial values. Qualitative values for each criterion were assigned for the lakes (see also Supplementary data - Appendix B, Table B.3).

Table 6 illustrates the results of the Bolivian GLOF risk assessment. Overall, one lake is identified as high risk (Murarata – Laguna Arkhata), and two lakes are identified as medium risk (Apolobamba – Pelechuco; Real – Laguna Glaciar). The remainder are graded as low risk.

4. Discussion

4.1. Comparisons with existing GLOF hazard and risk assessments

We assessed the level of GLOF risk for 16 lakes that had been identified in previous studies as representing a threat to downstream communities or infrastructure and found that our results were broadly consistent with those previous studies (Table 3). This is encouraging because our risk assessment model has been applied here to a range of

Table 6
Risk levels for potentially dangerous lakes in the Bolivian Andes as identified by Cook et al. (2016). Decimal percentages indicate the level of confidence that a lake belongs to the specific risk class (Low risk = Green, Medium risk = Orange, High risk = Red).

Lakes	Coordinates in UTM			Risk level
Apolobamba - Puina	19 L	476504	8384832	0.58
Apolobamba - Pelechuco	19 L	481205	8365591	0.84
Apolobamba - Hilo Hilo 1	19 L	492850	8354529	0.79
Apolobamba - Hilo Hilo 2	19 L	487996	8349572	0.91
Apolobamba - Hilo Hilo3	19 L	487666	8349316	0.78
Apolobamba - Puyo Puyo	19 L	486275	8351196	0.97
Apolobamba - Taypi Cayuma 1	19 L	491182	8343142	0.92
Apolobamba - Taypi Cayuma 2	19 L	492072	8340807	0.94
Apolobamba - Cholina Cholina 1	19 L	497085	8337363	0.78
Apolobamba - Cholina Cholina 2	19 L	498284	8335884	0.94
Real - Laguna Glaciar	19 L	547085	8249728	0.81
Real - Cocoyo 1	19 L	556846	8251418	0.94
Real - Cocoyo 2	19 L	559120	8249880	0.97
Real - Cocoyo 3	19 L	560553	8247486	0.58
Real - Rinconada 1	19 L	552071	8244232	0.58
Real - Rinconada 2	19 L	550069	8242190	0.58
Real - Laguna Wara Warani	19 K	567694	8222503	0.79
Real - Umapalca	19 K	584186	8220965	0.58
Real - Condoriri	19 K	578927	8210860	0.98
Real - Comunidad Pantini	19 K	612872	8182149	0.97
Mururata - Laguna Arkhata	19 K	624521	8172040	0.58
Tres Cruces - North	19 K	670245	8126070	0.91
Tres Cruces - Mining camp west	19 K	674446	8120893	0.57
Tres Cruzes - Mining camp east	19 K	678278	8121207	0.77
Tres Cruces - Laguna Huallatani	19 K	675910	8118767	0.77

regions and dam-types, whereas previous studies have generally focused on specific regions or specific lake or dam contexts. This widely applicable assessment is useful from a risk-management perspective because many glacierised landscapes contain a range of glacial lake types, and our model allows all lakes to be evaluated simultaneously. Specifically, we achieved the same results for Lake Hanpi K′ocha as did Frey et al. (2016), even though their risk assessment was based on field study and the use of criteria that cannot be evaluated in a desk-based study. Allen et al. (2009) focused only on hazard analysis rather than risk or impact assessment, but their outburst flood modelling results for Maud Lake and Godley Lake do not show any potential downstream impacts, which is consistent with the low risk rating from our MCDA method. Aggarwal et al. (2017) estimated Chholamo to represent a low GLOF susceptibility and Lake 0071 to represent a medium GLOF susceptibility, but both of those lakes are not upstream of important infrastructure or population, and hence are rated as low risk in our assessment. Worni et al. (2013) estimated that Gopang Gath and Spong Tongpo pose a medium level of risk, which agrees with our results. This is due mostly to the relatively low downstream population and the long runout distances required for flood impact to villages. In addition, triggering factors (TR.1, 2, 3) are graded as low in this area of the Himalaya. Worni et al. (2013) also assessed Schako Tsho and found that it posed a high level of risk, which agrees with our results. This rating is driven by intense precipitation events, steep slopes in close proximity to the lake, and the presence of nearby communities downstream. Rounce et al. (2016) assessed eight large Nepalese lakes with significant populations or infrastructure downstream. All eight lakes are in close proximity to steep slopes, most are in contact with parent glaciers, and there are potential triggers including seismic activity and intense precipitation events. The authors assessed the GLOF risk of most lakes to be high, with the exception of Imja Tsho, which was graded as medium risk, and Lower Barung Tsho, which was graded as very high risk. The authors underline that Imja Tsho will become high risk in the next 10 to 20 years because it is growing rapidly. Our model largely agrees with these results by classifying all of these lakes as high risk.

4.2. Comparisons of model results with GLOF-generating lakes

Table 3 also presents pre-GLOF risk assessments for seven lakes that have already generated GLOFs. This selection of GLOF-generating lakes comprises a mixture of ice, moraine and bedrock dams located in different regions around the world. Flatbreen lake burst in 2004 and generated a debris flow that reached the valley bottom ~1000 m below the lake (Breien et al., 2008). This lake is graded as low risk (a result that is sustained throughout the sensitivity analyses – Tables 4 and 5) due to both downstream impact parameters (IM.1 and IM.2) falling into the low impact category - there is no significant population or infrastructure in the immediate floodpath downstream (except farmland and a minor road). The Passu lake, Keara lake and lake 513 GLOF events are known to have damaged roads or bridges, or to have increased downstream sedimentation causing malfunction of water-treatment plants or damage to agricultural land (Ashraf et al., 2012; Carey et al., 2012; Hoffmann and Weggenmann, 2013; Klimeš et al., 2014; Vilímek et al., 2015). Nevertheless, they did not cause any casualties or fatalities. These factors are key drivers of the medium-risk classification from our MCDA method (Table 3). In contrast, Halji and Chorabari lakes are situated in relatively close proximity to downstream infrastructure and relatively high population numbers meaning that the overall risk was graded as high.

4.3. Potentially dangerous glacial lakes of the Bolivian Andes

GLOF risk was assessed for 25 lakes in the Bolivian Andes (Table 6). This represents the sort of situation where our model would be particularly valuable, i.e. in a region where GLOF risk has not yet been studied in detail, there are a range of lake types that need to be assessed simultaneously, and there are few data or observations to base decisions upon.

Our MCDA method reveals that 22 lakes represent low risk, mostly because of the low levels of downstream population and infrastructure, as well as the presence of bedrock dams, which are regarded as being more stable, and small estimated lake volumes. In addition, the glacierised area of the Cordillera Oriental, where these lakes are situated, is not a highly seismically active zone. Nevertheless, three lakes pose a more significant potential threat to downstream areas: the lake situated upstream from the village of Pelechuco, as well as Laguna Glaciar and Laguna Arkhata. Pelechuco lake and Laguna Glaciar are classified in our model as medium risk lakes with a high level of confidence, as shown in Table 6 (0.84 and 0.81 respectively). This can be explained by the high population downstream, and both seem to be susceptible to GLOFs since they are in contact with their parent glacier, and surrounded by steep slopes. Laguna Arkhata is the only lake classified as high risk, with a confidence level of 0.58. This is mostly due to its large size, the large population downstream, steep slopes surrounding the lake, and contact between the lake and parent glacier. Having completed the MCDA method, future work can now be directed more confidently towards intensive study of the three most dangerous lakes.

4.4. MCDA model sensitivity

To our knowledge, we have undertaken the first sensitivity analysis of any GLOF risk or hazard assessment model. Sensitivity analysis allows the strength of the model to be assessed, and the certainty of lake risk classification to be explored. Sensitivity analysis is readily undertaken in the SMAA-TRI software, which is a key benefit of our approach.

All medium and high-risk lakes have at least three criteria rated as high risk (except Gopang Gath, which possesses only two high risk criteria), which causes them to remain in or switch into a high-risk category when the cutting level is increased from 0.65 to 0.85 (Table 4). Low-risk lakes and Gopang Gath stand out in Table 4 because their risk classification remains stable for all or most of the sensitivity tests. All low-risk lakes are dominated by low-risk ratings for all criteria so that even as the λ-cutting level is increased (i.e. the model is made more conservative), their overall risk level remains low. Gopang Gath, on the other hand, has a high number (9 out of 13) of criteria rated as medium risk, and only two high risk and two low-risk criteria. Therefore, the lake has an overall rating of medium risk until the cutting level is raised to 0.85, where even then the high-risk classification has only a modest confidence value of 0.44 (with low risk at 0.28 and medium risk at 0.28) (Table 5). Crucially, sensitivity analysis can be used, as it is here, to identify those lakes that remain within the same risk class as the cutting level is increased, which gives confidence to the user in making risk management decisions (e.g. whether additional monitoring or remediation would be required), or to identify cases where lakes are close to a higher risk boundary after the initial assessment with a lower cutting level (i.e. lakes that switch class as the cutting level is increased), and to evaluate the confidence level of the risk classifications. Overall, a λ-cutting level of 0.65 should be sufficiently robust for general use or initial risk assessment.

One of the key benefits of the MCDA approach is the use of the Description Problem approach to decide upon appropriate GLOF risk assessment criteria. However, the choice of thresholds for each criterion remains uncertain in some cases (see also Supplementary data - Appendix A). Hence, we also explored the effect of changing the threshold values for the high-risk category of each criterion (Table 5). For the most part, Table 5 illustrates that alteration of the thresholds for most criteria yields relatively few changes in risk categorization for each lake in our sample. This is due in large part to the fact that many of the lakes in our sample already fall into the high-risk category for each criterion, meaning that a relaxation of the criteria for high risk has little effect on the results. Nevertheless, there are a few notable exceptions. By relaxing the seismic activity (TR.1) high-risk threshold, 4 lakes are re-graded as high risk. However, this probably constitutes an unrealistic reclassification whereby mountain ranges with modest or low seismic activity are ascribed a higher risk rating. Risk managers and geoscientists should be able to gain sufficiently accurate information on regional seismic activity that they can attain appropriate thresholds and classifications, and the sensitivity analysis here gives us greater confidence that our original risk thresholds were already robust and realistic. Another exception is lake volume (SR.2) where the relaxation of the high-risk threshold results in three lakes being re-graded as high risk. Lake volume is an example of a criterion where it can be hard to determine where the thresholds should lie – in essence, it is hard to say what constitutes a large, medium or small lake. Our original lake volume classification (Table 2) is derived from a global glacial lake dataset (Cook and Quincey, 2015) that includes water bodies ranging in size from supraglacial ponds (0.1×10^6 m^3) to very large lakes (770×10^6 m^3) (see also Supplementary data - Appendix A). Our thresholds were informed by plotting a frequency distribution of the dataset presented in Cook and Quincey (2015). By relaxing the high-risk threshold, any lake with a size of 1×10^6 m^3 or larger is classified as high risk, which captures most of the lakes in our sample set. Given that the lake might not drain completely during a GLOF event, this revised threshold might be regarded as being overly conservative. Again, our sensitivity analysis gives us confidence that our original threshold was appropriate. Finally, relaxation of the GLOF travel distance high-risk threshold (SR.1) also causes three lakes to be re-graded as high risk. Our original threshold system was informed by previous studies (Huggel et al., 2002; Hegglin and Huggel, 2008) that adopted an empirical approach to defining the critical slope for clear water and debris-laden GLOF runout. Given this empirical basis, our sensitivity analysis here merely explores a very conservative threshold system, although risk managers may wish to use this system if there are large uncertainties about topography or the nature of the potential flood (e.g. whether sediment is likely to be entrained into a debris flow).

A small number of lakes, including Lake 513 and Passu Lake, are readily reclassified when the high-risk threshold is relaxed for some criteria (including TR.1, ME.3, SR.1, SR.2, IM.1). These lakes may need particular attention from risk managers, as they appear to be borderline cases. Fortunately, sensitivity analysis is able to reveal such cases.

4.5. The use of MCDA in GLOF risk assessments

Several previous studies (Huggel et al., 2004; Bolch et al., 2008; Mergili and Schneider, 2011; Emmer and Vilímek, 2013; Worni et al., 2013; Rounce et al., 2016) have provided important frameworks by which to assess GLOF hazard or risk. Since these are typically designed for particular sites or regions, and/or for specific lake types, they are already likely to provide robust risk and hazard assessments in those situations. However, risk managers in some regions may be presented with situations where a range of lake types may exist, and it is desirable to assess the relative level of hazard or risk between these lakes simultaneously. For example, a risk or hazard assessment designed for moraine-dammed lakes cannot necessarily be used to assess the risk or threat posed by ice-dammed or bedrock-dammed lakes. In this study, we have presented an MCDA approach that offers several key benefits for GLOF hazard and risk assessment that make it particularly useful in such situations. In common with some, but not all, previous studies (Fujita et al., 2008; Bolch et al., 2011; Aggarwal et al., 2016; Petrov et al., 2017), our MCDA approach uses free and widely available datasets or inputs, and there is no need for the inclusion of any field data – all of the information can be gathered and processed remotely as a desk-based study. Certainly, additional field-based data or higher resolution satellite imagery or elevation data would be advantageous, and could be incorporated into the MCDA model, but we have shown here, through comparisons with previous studies and sensitivity analyses, that this approach is already robust. Our approach would be particularly useful in serving as an initial survey for an area with several lake types in order to identify particularly dangerous lakes that might require further detailed study (e.g. fieldwork, hydrological modelling, remediation, monitoring). The MCDA approach presented here is a two-stage process, whereby a Description Problem is addressed first, before a Sorting Problem is completed. The formulation of the Description Problem represents another key benefit compared to previous GLOF risk and hazard assessments. Firstly, and in common with some previous reviews on GLOF initiation and impacts (e.g. Emmer and Vilímek, 2013; Rounce et al., 2016), it forces a comprehensive review of all factors that could drive a glacial lake towards becoming dangerous (Fig. 1 and Tables 1 and 2). Crucially, however, the principles of MCDA (Section 2.1) mean that the criteria selected to assess GLOF risk are exhaustive, non-redundant, and consistent. Many previous studies have kept, for example, one composite criterion instead of splitting it into multiple criteria, therefore potentially biasing the analysis.

The use of the SMAA-TRI software has some specific advantages. Firstly, it is freely available, but it is also straightforward to use, and it has a means of testing the strength of results through the generation of confidence measures and sensitivity analyses, as outlined in this study. Further, although we have opted for a Sorting Problem approach, the use of SMAA-2 (which can be found in the same download package; http://smaa.fi/) allows the construction of a Ranking Problem, which may be useful for other practitioners with different requirements.

Our MCDA approach, through the construction of a Description Problem (Section 2.2), streamlines the wide array of criteria that have been used previously to assess GLOF risk. Nonetheless, since our approach offers a rapid, first pass assessment of GLOF risk, the final 13 criteria used inevitably ignore some criteria that cannot be assessed remotely (e.g. vulnerability factors, specific details about the nature of the dam). Hence, there remain situations where it would be advantageous to use existing GLOF risk assessments that have been tailored to specific lakes, regions or contexts, or where field data are available to be incorporated into the risk assessment to address particular criteria.

There remain a number of challenges for those constructing and using GLOF risk and hazard assessments. Firstly, the thresholds used to define risk categories are uncertain. For the most part, we have borrowed thresholds for each criterion based on previous work (see also Supplementary data - Appendix A), and this then reflects some degree of consensus among the GLOF risk community about how to assess GLOF risk. But some values might be questioned. For example, how big is a big (high-risk) lake? How steep is a steep (high-risk) slope that could shed ice or rock mass movements into the lake? Should we use potential loss of life thresholds that could be applicable to mass casualty events, such as tsunamis and earthquakes, where many thousands of people could lose their lives, or should we use lower thresholds considering that most GLOF-affected environments are relatively sparsely populated? Another unsolved problem is the weighting for each of the criteria used. At this stage, it is impossible to tell whether some criteria are more important than others, with the exception perhaps of loss of life and damage to infrastructure.

5. Conclusion

For the first time, we have undertaken a risk assessment for glacial lake outburst floods (GLOFs) using a Multi-Criteria Decision Analysis (MCDA) approach. MCDA has been applied to several natural hazard and risk contexts, but never before to GLOFs. Whilst several previous studies have outlined GLOF hazard and risk assessment procedures, we argue that the MCDA method has a number of benefits to offer. The MCDA approach (1) uses freely and widely available data inputs and software, without the requirement for field-based study; (2) can be applied across a range of glacial lake contexts (ice-dammed, moraine-dammed, etc.) simultaneously, and to any region of the world; (3) enables researchers to make a first-pass analysis of potentially dangerous lakes objectively before committing to further investigation (e.g. field work, remote sensing data analysis); and (4) readily permits sensitivity testing of the model. Crucially, the first stage of the MCDA approach (the Description Problem) involves the determination of appropriate criteria by which to define risk. The principles of MCDA require the use of exhaustive, non-redundant, and consistent criteria, which can be regarded as a key benefit of this approach. For example, previous assessment procedures have sometimes double-counted, ignored, or selected criteria subjectively or non-transparently (McKillop and Clague, 2007a, 2007b).

We assessed the risk of 16 potentially dangerous glacial lakes as well as 6 lakes that have already generated GLOFs in the past (between 2004 and 2013). Our results for the 16 extant lakes compare favourably with previous risk and hazard assessments, which have generally focused on specific regions or glacial lake contexts. This indicates that our MCDA model can be applied in a range of contexts globally. Further, we undertook sensitivity analyses of our model to explore the robustness of results and model assumptions. To our knowledge, this is the first time sensitivity analysis has been performed for a GLOF risk or hazard assessment model. Two sensitivity analyses were undertaken. In the first, the proportion of criteria that need to be graded as 'high risk' in order to grade the overall risk as 'high' was relaxed (the so-called 'λ-cutting level'). This identified several lakes that remain within the same risk class as this cutting level is increased, which gives confidence to the user in making risk management decisions about those lakes. The second sensitivity test involved relaxing the threshold for 'high risk' for each criterion. This generally revealed that the original risk thresholds used here were robust, although some lakes were identified that might warrant further study because they changed readily to a higher risk class. We applied the tested method on 25 glacial lakes in the data-scarce Bolivian Andes, and found that 22 of these lakes represent low risk, and therefore do not currently require further attention. Nevertheless, further detailed investigation or action is required for two lakes rated as medium risk (Pelechuco, Laguna Glaciar), and one lake rated as high risk (Laguna Arkhata).

We suggest that our MCDA approach would be best suited to identifying potentially dangerous lakes in regions where a range of glacial lake types may exist, such as demonstrated here for the Bolivian Andes. Our method allows the relative risk of these different lakes to be assessed simultaneously, and takes account of both GLOF susceptibility and potential impacts.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: https://doi.org/10.1016/j.scitotenv.2017.10.083. These data include the Google maps of the most important areas described in this article.

References

Aggarwal, A., Jain, S.K., Lohani, A.K., Jain, N., 2016. Glacial lake outburst flood risk assessment using combined approaches of remote sensing, GIS and dam break modelling. Geomatics, Nat. Hazards Risk 7:18–36. https://doi.org/10.1080/19475705.2013.862573.

Aggarwal, S., Rai, S.C., Thakur, P.K., Emmer, A., 2017. Inventory and recently increasing (GLOF) susceptibility of glacial lakes in Sikkim, Eastern Himalaya. Geomorphology https://doi.org/10.1016/j.geomorph.2017.06.014.

Akgun, A., Türk, N., 2010. Landslide susceptibility mapping for Ayvalik (Western Turkey) and its vicinity by multicriteria decision analysis. Environ. Earth Sci. 61:595–611. https://doi.org/10.1007/s12665-009-0373-1.

Allen, S.K., Schneider, D., Owens, I.F., 2009. First approaches towards modelling glacial hazards in the mount cook region of New Zealand's southern alps. Nat. Hazards Earth Syst. Sci. 9:481–499. https://doi.org/10.5194/nhess-9-481-2009.

Allen, S.K., Rastner, P., Arora, M., Huggel, C., Stoffel, M., 2015. Lake outburst and debris flow disaster at Kedarnath, June 2013: hydrometeorological triggering and topographic predisposition. Landslides 1–13.

Allen, S.K., Linsbauer, A., Randhawa, S.S., Huggel, C., Rana, P., Kumari, A., 2016. Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. Nat. Hazards:1–23 https://doi.org/10.1007/s11069-016-2511-x.

Anacona, P.I., Mackintosh, A., Norton, K., 2015. Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia: lessons for GLOF risk management. Sci. Total Environ. 527–528:1–11. https://doi.org/10.1016/j.scitotenv.2015.04.096.

Ashraf, A., Naz, R., Roohi, R., 2012. Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan Ranges of Pakistan: implications and risk analysis. Geomatics, Nat. Hazards Risk 3:113–132. https://doi.org/10.1080/19475705.2011.615344.

Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M., 2010. PROMETHEE: a comprehensive literature review on methodologies and applications. Eur. J. Oper. Res. 200: 198–215. https://doi.org/10.1016/j.ejor.2009.01.021.

Benn, D.I., Wiseman, S., Hands, K.A., 2001. Growth and drainage of supraglacial lakes on debris-mantled Ngozumpa glacier, Khumbu Himal, Nepal. J. Glaciol. 47:626–638. https://doi.org/10.3189/172756501781831729.

Bolch, T., Buchroithner, M.F., Peters, J., Baessler, M., Bajracharya, S., 2008. Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. Nat. Hazards Earth Syst. Sci. 8:1329–1340. https://doi.org/10.5194/nhess-8-1329-2008.

Bolch, T., Peters, J., Yegorov, A., Pradhan, B., Buchroithner, M., Blagoveshchensky, V., 2011. Identification of potentially dangerous glacial lakes in the northern Tian Shan. Nat. Hazards 59:1691–1714. https://doi.org/10.1007/978-3-642-25495-6_12.

Breien, H., De Blasio, F.V., Elverhøi, A., Høeg, K., 2008. Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway. Landslides 5:271–280. https://doi.org/10.1007/s10346-008-0118-3.

Brito, M.M. De, Evers, M., 2016. Multi-criteria Decision-making for Flood Risk Management: A Survey of the Current State of the Art. :pp. 1019–1033 https://doi.org/10.5194/nhess-16-1019-2016.

Brito, A.J., de Almeida, A.T., Mota, C.M.M., 2010. A multicriteria model for risk sorting of natural gas pipelines based on ELECTRE TRI integrating utility theory. Eur. J. Oper. Res. 200:812–821. https://doi.org/10.1016/j.ejor.2009.01.016.

Carey, M., Huggel, C., Bury, J., Portocarrero, C., Haeberli, W., 2012. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. Clim. Chang. 112:733–767. https://doi.org/10.1007/s10584-011-0249-8.

Carrivick, J.L., Tweed, F.S., 2013. Proglacial Lakes: character, behaviour and geological importance. Quat. Sci. Rev. 78:34–52. https://doi.org/10.1016/j.quascirev.2013.07.028.

Carrivick, J.L., Tweed, F.S., 2016. A global assessment of the societal impacts of glacier outburst floods. Glob. Planet. Chang. 144:1–16. https://doi.org/10.1016/j.gloplacha.2016.07.001.

Chen, K., Blong, R., Jacobson, C., 2001. MCE-RISK: integrating multicriteria evaluation and GIS for risk decision-making in natural hazards. Environ. Model. Softw. 16:387–397. https://doi.org/10.1016/S1364-8152(01)00006-8.

Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary science reviews a review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat. Sci. Rev. 19:1763–1783. https://doi.org/10.1016/S0277-3791(00)00090-1.

Cook, S.J., Quincey, D.J., 2015. Estimating the volume of alpine glacial lakes. Earth Surf. Dyn. 3:559–575. https://doi.org/10.5194/esurf-3-559-2015.

Cook, S.J., Kougkoulos, I., Edwards, L.A., Dortch, J., Hoffmann, D., 2016. Glacier change and glacial lake outburst flood risk in the Bolivian Andes. Cryosphere 10:2399–2413. https://doi.org/10.5194/tc-10-2399-2016.

Costa, Schuster, 1988. The formation and failure of natural dams. America Bulletin]–>Geol. Soc. Am. Bull. 100, 1054–1068.

Damart, S., Dias, L.C., Mousseau, V., 2007. Supporting groups in sorting decisions: methodology and use of a multi-criteria aggregation/disaggregation DSS. Decis. Support. Syst. 43:1464–1475. https://doi.org/10.1016/j.dss.2006.06.002.

Das, S., Kar, N.S., Bandyopadhyay, S., 2015. Glacial lake outburst flood at Kedarnath, Indian Himalaya: a study using digital elevation models and satellite images. Nat. Hazards 77:769–786. https://doi.org/10.1007/s11069-015-1629-6.

Emmer, A., Vilímek, V., 2013. Review article: Lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). Nat. Hazards Earth Syst. Sci. 13:1551–1565. https://doi.org/10.5194/nhess-13-1551-2013.

Emmer, A., Vilímek, V., 2014. New method for assessing the susceptibility of glacial lakes to outburst floods in the Cordillera Blanca, Peru. Hydrol. Earth Syst. Sci. 18: 3461–3479. https://doi.org/10.5194/hess-18-3461-2014.

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V., Cochachin, A., 2016a. 882 lakes of the Cordillera Blanca: an inventory, classification, evolution and assessment of susceptibility to outburst floods. Catena 147:269–279. https://doi.org/10.1016/j.catena.2016.07.032.

Figueira, J., Roy, B., 2002. Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. Eur. J. Oper. Res. 139:317–326. https://doi.org/10.1016/S0377-2217(01)00370-8.

Figueira, J., Greco, S., Roy, B., Słowiński, R., 2013. An overview of ELECTRE methods and their recent extensions. J. Multi-Criteria Decis. Anal. 20:61–85. https://doi.org/10.1002/mcda.1482.

Frey, H., Huggel, C., Paul, F., Haeberli, W., 2010. Automated Detection of Glacier Lakes Based on Remote Sensing in View of Assessing Associated Hazard Potentials. Proc. 10th Int. sympsoium high Mt. Remote sending Cartogr. pp. 23–30.

Frey, H., Huggel, C., Bühler, Y., Buis, D., Burga, M.D., Choquevilca, W., Fernandez, F., García Hernández, J., Giráldez, C., Loarte, E., Masias, P., Portocarrero, C., Vicuña, L., Walser, M., 2016. A robust debris-flow and GLOF risk management strategy for a data-scarce catchment in Santa Teresa, Peru. Landslides https://doi.org/10.1007/s10346-015-0669-z.

Fujita, K., Suzuki, R., Nuimura, T., Sakai, A., 2008. Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya. J. Glaciol. 54:220–228. https://doi.org/10.3189/002214308784886162.

Grabs, W.E., Hanisch, J., 1992. Objectives and prevention methods for glacier Lake outburst moods (GLOFs). Snow Glacier Hydrol. 218, 341–352.

Hegglin, E., Huggel, C., 2008. An integrated assessment of vulnerability to glacial hazards. Mt. Res. Dev. 28:299–309. https://doi.org/10.1659/mrd.0976.

Hoffmann, D., Weggenmann, D., 2013. Climate change induced glacier retreat and risk management: glacial Lake outburst floods (GLOFs) in the Apolobamba Mountain Range, Bolivia. Chang. Disaster Risk Manag.:71–87 https://doi.org/10.1007/978-3-642-31110-9_5.

Huang, I.B., Keisler, J., Linkov, I., 2011. Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. Sci. Total Environ. 409:3578–3594. https://doi.org/10.1016/j.scitotenv.2011.06.022.

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., Paul, F., 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss alps. Can. Geotech. J. 39:316–330. https://doi.org/10.1139/t01-099.

Huggel, C., Haeberli, W., Kääb, A., Bieri, D., Richardson, S., 2004. An assessment procedure for glacial hazards in the Swiss alps. Can. Geotech. J. 41:1068–1083. https://doi.org/10.1139/t04-053.

ICIMOD, 2011. Glacial Lakes and Glacial Lake Outburst Floods in Nepal. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu.

IPCC, 2014. Summary for Policymakers. Working Group II Contribution to the IPCC Fifth Assessment Report Climate Change 2014: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, UK.

Ishizaka, A., Pearman, C., Nemery, P., 2012. AHPSort: an AHP-based method for sorting problems. Int. J. Prod. Res. 50:4767–4784. https://doi.org/10.1080/00207543.2012.657966.

ISO 31000:2009, 2009. Risk Management — Principles and Guidelines. International Organization for Standardization, Geneva, Switzerland.

Ives, J.D., Shrestha, R.B., Mool, P.K., 2010. Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment. Kathmandu, ICIMOD.

Klimeš, J., Benešová, M., Vilímek, V., Bouška, P., Cochachin Rapre, A., 2014. The reconstruction of a glacial lake outburst flood using HEC-RAS and its significance for future hazard assessments: an example from Lake 513 in the Cordillera Blanca, Peru. Nat. Hazards 71:1617–1638. https://doi.org/10.1007/s11069-013-0968-4.

Kropáček, J., Neckel, N., Tyrna, B., Holzer, N., Hovden, A., Gourmelen, N., Schneider, C., Buchroithner, M., Hochschild, V., 2015. Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in North-Western Nepal. Nat. Hazards Earth Syst. Sci. 15:2425–2437. https://doi.org/10.5194/nhess-15-2425-2015.

Lin, W.T., 2008. Earthquake-induced landslide hazard monitoring and assessment using SOM and PROMETHEE techniques: a case study at the Chiufenershan area in Central Taiwan. Int. J. Geogr. Inf. Sci. 22:995–1012. https://doi.org/10.1080/13658810801914458.

Malczewski, J., Rinner, C., 2015. Multicriteria decision analysis in geographic information science. Anal. Methods https://doi.org/10.1007/978-3-540-74757-4.

Marinoni, O., 2005. A stochastic spatial decision support system based on PROMETHEE. Int. J. Geogr. Inf. Sci. 19:51–68. https://doi.org/10.1080/13658810412331280176.

McKillop, R.J., Clague, J.J., 2007a. Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia. Glob. Planet. Chang. 56:153–171. https://doi.org/10.1016/j.gloplacha.2006.07.004.

McKillop, R.J., Clague, J.J., 2007b. A procedure for making objective preliminary assessments of outburst flood hazard from moraine-dammed lakes in southwestern British Columbia. Nat. Hazards 41:131–157. https://doi.org/10.1007/s11069-006-9028-7.

Merad, M.M., Verdel, T., Roy, B., Kouniali, S., 2004. Use of multi-criteria decision-aids for risk zoning and management of large area subjected to mining-induced hazards. Tunn. Undergr. Sp. Technol. 19:125–138. https://doi.org/10.1016/S0886-7798(03)00106-8.

Mergili, M., Schneider, J.F., 2011. Regional-scale Analysis of Lake Outburst Hazards in the Southwestern Pamir, Tajikistan, Based on Remote Sensing and GIS. :pp. 1447–1462 https://doi.org/10.5194/nhess-11-1447-2011.

Mertes, J.R., Thompson, S.S., Booth, A.D., Gulley, J.D., Benn, D.I., 2016. A conceptual model of supra-glacial lake formation on debris-covered glaciers based on GPR facies analysis. Earth Surf. Process. Landf. https://doi.org/10.1002/esp.4068.

Mousseau, V., Slowinski, R., Zielniewicz, P., 2000. A user-oriented implementation of the ELECTRE-TRI method integrating preference elicitation support. Comput. Oper. Res. 27:757–777. https://doi.org/10.1016/S0305-0548(99)00117-3.

Nemery, P., Lamboray, C., 2008. Flow sort: a flow-based sorting method with limiting or central profiles. TOP 16:90–113. https://doi.org/10.1007/s11750-007-0036-x.

O'Connor, J.E., Hardison III, J.H., Costa, J.E., 2001. Debris flows from failures of Neoglacial-Age Moraine Dams in the Three Sisters and Mount Jefferson Wilderness Areas. USGS Professional Paper, Oregon.

Petrov, M.A., Sabitov, T.Y., Tomashevskaya, I.G., Glazirin, G.E., Chernomorets, S.S., Savernyuk, E.A., Tutubalina, O.V., Petrakov, D.A., Sokolov, L.S., Dokukin, M.D., Mountrakis, G., Ruiz-Villanueva, V., Stoffel, M., 2017. Glacial lake inventory and lake outburst potential in Uzbekistan. Sci. Total Environ. 592:228–242. https://doi.org/10.1016/j.scitotenv.2017.03.068.

Reynolds, J.M., 2003. Development of Glacial Hazard and Risk Minimisation Protocols in Rural Environments Methods of Glacial Hazard Assessment and Management in the Cordillera Blanca, Peru April 2003 Project No: R7816. H.

Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. Quat. Int. 65–66:31–47. https://doi.org/10.1016/S1040-6182(99)00035-X.

Rickenmann, D., 1999. Empirical relationships for debris flows. Nat. Hazards 19, 47–77.

Rickenmann, D., 2005. Runout prediction methods. In: Jakob, M., Hungr, O. (Eds.), Debris-flow hazards and related phenomena. Springer, Berlin/Heidelberg, pp. 305–324.

Rounce, D.R., McKinney, D.C., Lala, J.M., Byers, A.C., Watson, C.S., 2016. A new remote hazard and risk assessment framework for Glacial Lakes in the Nepal Himalaya. Hydrol. Earth Syst. Sci. Discuss.:1–48 https://doi.org/10.5194/hess-2016-161.

Roy, B., 1993. Decision science or decision aid science? Eur. J. Oper. Res. 66, 184–203.

Roy, B., 1996. Multicriteria Methodology for Decision Analysis. Kluwer, Dordrecht.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. J. Math. Psychol. 15:234–281. https://doi.org/10.1016/0022-2496(77)90033-5.

Saltelli, A., Tarantola, S., Chan, K., 1999. A role for sensitivity analysis in presenting the results from MCDA studies to decision makers. J. Multi-Criteria Decis. Anal. 145, 139–145.

Sánchez-Lozano, J.M., Henggeler Antunes, C., García-Cascales, M.S., Dias, L.C., 2014. GIS-based photovoltaic solar farms site selection using ELECTRE-TRI: evaluating the case for Torre Pacheco, Murcia, Southeast of Spain. Renew. Energy 66:478–494. https://doi.org/10.1016/j.renene.2013.12.038.

Stecchi, F., Mancini, F., Ceppi, C., Gabbianelli, G., 2012. Vulnerability to ground deformation phenomena in the city of Tuzla (BiH): a GIS and multicriteria approach. Nat. Hazards 64:2153–2165. https://doi.org/10.1007/s11069-012-0225-2.

Tacnet, J.M., Dezert, J., Curt, C., Batton-Hubert, M., Chojnacki, E., 2014. How to manage natural risks in mountain areas in a context of imperfect information? New frameworks and paradigms for expert assessments and decision-making. Environ. Syst. Decis. 34: 288–311. https://doi.org/10.1007/s10669-014-9501-x.

Tervonen, T., 2012. JSMAA: open source software for SMAA computations. Int. J. Syst. Sci. 45:69–81. https://doi.org/10.1080/00207721.2012.659706.

Thompson, S.S., Benn, D.I., Dennis, K., Luckman, A., 2012. A rapidly growing moraine-dammed glacial lake on Ngozumpa glacier, Nepal. Geomorphology 145–146:1–11. https://doi.org/10.1016/j.geomorph.2011.08.015.

Tweed, F.S., Russell, A.J., 1999. Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. Prog. Phys. Geogr. 23: 79–110. https://doi.org/10.1191/030913399666727306.

Vilímek, V., Klimeš, J., Emmer, A., Benešová, M., 2015. Geomorphologic impacts of the glacial lake outburst flood from lake no. 513 (Peru). Environ. Earth Sci. 73:5233–5244. https://doi.org/10.1007/s12665-014-3768-6.

Wang, X., Liu, S., Guo, W., Xu, J., 2008. Assessment and simulation of glacier Lake outburst floods for Longbasaba and Pida Lakes, China. Mt. Res. Dev. 28:310–317. https://doi.org/10.1659/mrd.0894.

Wang, W., Yao, T., Gao, Y., Yang, X., Kattel, D.B., 2011. A first-order method to identify potentially dangerous Glacial Lakes in a region of the southeastern Tibetan plateau. Mt. Res. Dev. 31:122–130. https://doi.org/10.1659/MRD-JOURNAL-D-10-00059.1.

Wang, S., Qin, D., Xiao, C., 2015. Moraine-dammed lake distribution and outburst flood risk in the Chinese Himalaya. J. Glaciol. 61:115–126. https://doi.org/10.3189/2015JoG14J097.

Watson, C.S., Carrivick, J., Quincey, D., 2015. An improved method to represent DEM uncertainty in glacial lake outburst flood propagation using stochastic simulations. J. Hydrol. 529:1373–1389. https://doi.org/10.1016/j.jhydrol.2015.08.046.

Worni, R., Huggel, C., Stoffel, M., 2013. Glacial lakes in the Indian Himalayas—from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. Sci. Total Environ. 468–469:S71–84. https://doi.org/10.1016/j.scitotenv.2012.11.043.

Zapata, M.L., 2002. La dinamica glaciar en lagunas de la Cordillera Blanca. Acta Montana 19, 37–60.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A.P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L.N., Càceres, B.E., Casassa, G., Cobos, G., Dàvila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V., Portocarrero, C.A., Prinz, R., Sangewar, C.V., Severskiy, I., Sigurdsson, O., Soruco, A., Usubaliev, R., Vincent, C., 2015. Historically unprecedented global glacier decline in the early 21st century. J. Glaciol. 61:745–762. https://doi.org/10.3189/2015JoG15J017.

Appendix 1.2.

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ORIGINAL PAPER

Modelling glacial lake outburst flood impacts in the Bolivian Andes

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Abstract
The Bolivian Andes have experienced sustained and widespread glacier mass loss in recent decades. Glacier recession has been accompanied by the development of proglacial lakes, which pose a glacial lake outburst flood (GLOF) risk to downstream communities and infrastructure. Previous research has identified three potentially dangerous glacial lakes in the Bolivian Andes, but no attempt has yet been made to model GLOF inundation downstream from these lakes. We generated 2-m resolution DEMs from stereo and tri-stereo SPOT 6/7 satellite images to drive a hydrodynamic model of GLOF flow (HEC-RAS 5.0.3). The model was tested against field observations of a 2009 GLOF from Keara, in the Cordillera Apolobamba, and was shown to reproduce realistic flood depths and inundation. The model was then used to model GLOFs from Pelechuco lake (Cordillera Apolobamba) and Laguna Arkhata and Laguna Glaciar (Cordillera Real). In total, six villages could be affected by GLOFs if all three lakes burst. For sensitivity analysis, we ran the model for three scenarios (pessimistic, intermediate, optimistic), which give a range of ~1100 to ~2200 people affected by flooding; between ~800 and ~2100 people could be exposed to floods with a flow depth ≥2 m, which could be life threatening and cause a significant damage to infrastructure. We suggest that Laguna Arkhata and Pelechuco lake represent the greatest risk due to the higher numbers of people who live in the potential flow paths, and hence, these two glacial lakes should be a priority for risk managers.

Keywords Bolivian Andes · Geohazards · Glacial lake outburst floods (GLOFs) · Hydrodynamic modelling · Risk assessment

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1 Introduction

Climate change is driving glacier mass loss in most parts of the world (Zemp et al. 2015). In many cases, glaciers recede into bedrock basins, or behind moraine dams, leading to meltwater ponding in proglacial lakes; meltwater can also pond supraglacially, especially on debris-covered glaciers (Cook and Swift 2012; Cook and Quincey 2015; Carrivick and Tweed 2013). Several studies have documented increases in the number and size of such lakes in recent decades (Komori 2008; Carrivick and Tweed 2013; Hanshaw and Bookhagen 2014; López-Moreno et al. 2014; Wang et al. 2015a). Glacial lakes can burst as a consequence of reduction in the integrity of the dam over time (e.g. from piping, mass movements on the dam flanks, or melting of ice within the dam), impact from ice, snow or rock avalanches entering the lake, glaciers calving into the lake, or seismic activity (Richardson and Reynolds 2000; Westoby et al. 2014b). Consequently, there has been growing concern about the impacts of glacial lake outburst floods (GLOFs) on downstream communities and infrastructure in many deglaciating regions worldwide (e.g. Vilímek et al. 2013; Carrivick and Tweed 2016; Emmer et al. 2016).

GLOF risk in Bolivia has received very little attention despite an event having occurred here in 2009, when an ice-dammed lake drained catastrophically, impacting the village of Keara in the Cordillera Apolobamba (Hoffmann and Weggenmann 2013). Recent work by Cook et al. (2016) found that glacier area in the Bolivian Andes had reduced by ~43% from 1986 to 2014, leading to an increase in the number and areal coverage of proglacial lakes. They undertook a rudimentary assessment of GLOF risk in the region, suggesting that 25 lakes could pose a risk to downstream communities. Subsequent work by Kougkoulos et al. (2018) developed a GLOF risk assessment technique based on the use of multi-criteria decision analysis (MCDA), which was applied to the lake inventory of Cook et al. (2016). Kougkoulos et al. (2018) found that two lakes represented 'medium' risk and one lake represented 'high' risk. In this study, we aim to model potential GLOF inundation downstream from these three lakes and assess the possible impacts on downstream communities and infrastructure.

2 Geographical setting and methods

2.1 Geographical setting

This study focused on the glaciated ranges of the Cordillera Oriental, Bolivia; from north to south these are the Cordillera Apolobamba, the Cordillera Real (including Huayna Potosí, Mururata, Illimani), and the Cordillera Tres Cruces (Fig. 1). The three lakes identified by Kougkoulos et al. (2018) as having the highest risk include Laguna Arkhata, Pelechuco Lake, and Laguna Glaciar (Fig. 1). The only documented GLOF in Bolivia occurred at Keara (Fig. 1), which serves as a test case for our modelling approach. The Keara GLOF took place on 3 November 2009 at about 11:00 a.m. local time and involved the complete drainage of an ice-dammed lake (Hoffmann and Weggenmann 2013). This event flooded cultivated fields, destroyed several kilometres of a local dirt road, washed away pedestrian bridges, and killed a number of farm animals (Hoffmann and Weggenmann 2013). Fortunately, there were no human fatalities.

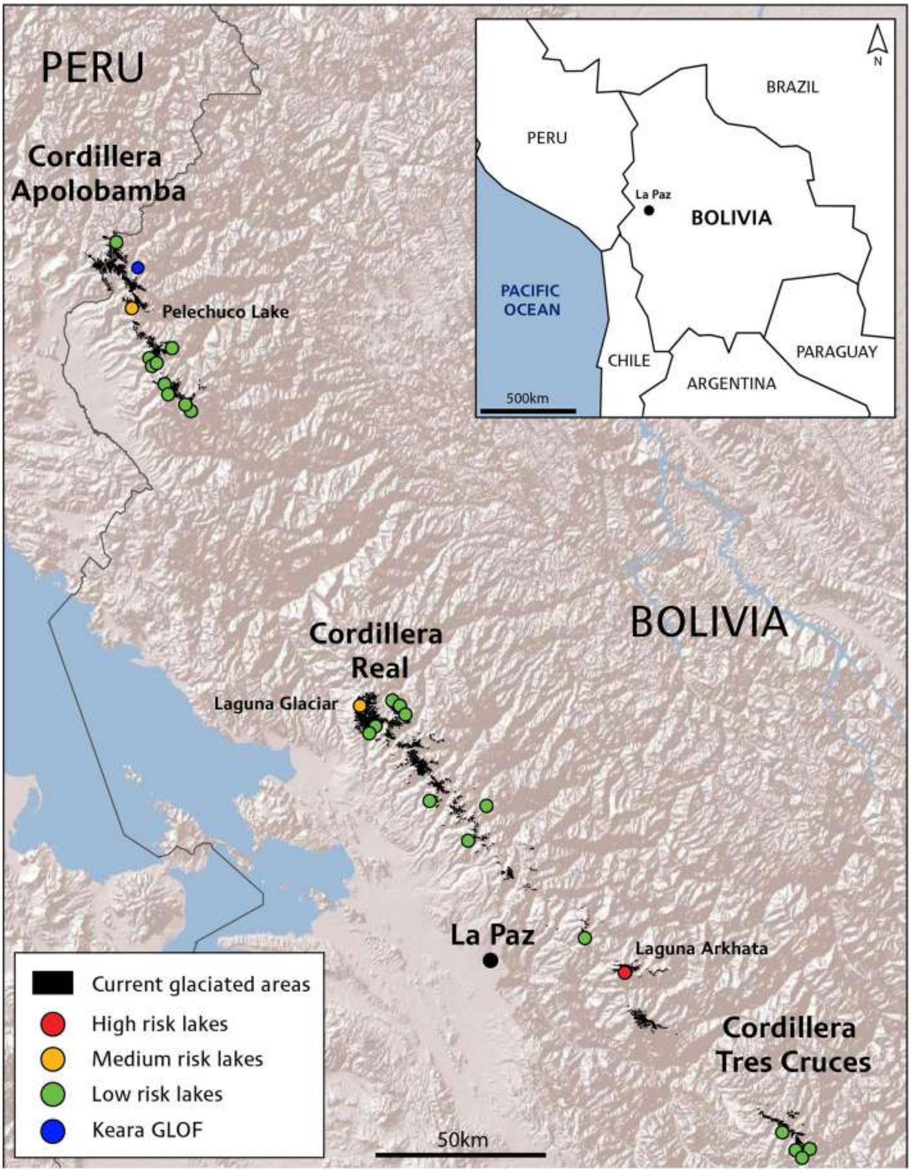

Fig. 1 Location of glaciers and potentially dangerous glacial lakes in the Bolivian Andes, as well as the 2009 Keara GLOF event. The risk of each glacial lake identified by Cook et al. (2016) was assessed by Kougkoulos et al. (2018) using the MCDA methodology; three lakes were graded as 'medium' (orange) and 'high' risk (red) and form the focus of this study

Information about the lakes discussed in this study (e.g. coordinates, measured areas, estimated volumes) is presented in Table 1. The lakes exist in the same region (Cordillera Oriental) and so are subject to similar environmental conditions (e.g. regional seismic activity, intense precipitation events, high-temperature events). However, these lakes were found by Kougkoulos et al. (2018) to be more susceptible than other glacial lakes in the

Table 1 Parameter values used for the three different scenario simulations in HEC-RAS

Lake (coordinates in UTM)	Scenario	Outburst duration (s)	Manning's value	Lake area (m^2)	Estimated lake depth (m)	Lake volume (m^3)	Drainage percentage (%)	Total discharge volume (m^3)	Q_{max} ($m^3\ s^{-1}$)
Keara lake (19L 481958 8377253)	Optimistic	1000	0.05	34,000	4	136,783	100	136,783	458
	Intermediate	1500	0.04		8	261,088	100	261,088	609
	Pessimistic	2000	0.03		11	385,394	100	385,394	723
Pelechuco lake (19L 481205 8365591)	Optimistic	1000	0.05	80,000	12	996,890	20	199,378	464
	Intermediate	1500	0.04		15	1,209,618	50	604,809	835
	Pessimistic	2000	0.03		18	1,422,346	100	1,422,346	1313
Laguna Glaciar (19L 5470858249728)	Optimistic	1000	0.05	328,600	19	6,382,045	20	1,276,409	1240
	Intermediate	1500	0.04		23	7,500,896	50	3,750,448	2196
	Pessimistic	2000	0.03		26	8,619,746	100	8,619,746	3413
Laguna Arkhata (19K 624521 8172040)	Optimistic	1000	0.05	699,200	30	20,835,270	20	4,167,054	2322
	Intermediate	1500	0.04		34	23,993,347	50	11,996,674	4067
	Pessimistic	2000	0.03		39	27,151,425	100	27,151,425	6270

To estimate Q_{max} for the Keara Lake, Walder and Costa equation for non-tunnel floods (1996) was used. Evans (1986) was used for the remaining three lakes. Drainage percentage remains at 100% in Keara because the entire lake drained during the 2009 GLOF event region because of local conditions that control potential GLOF triggering mechanisms. We provide some information about these potential triggers in the subsequent subsections.

2.1.1 Pelechuco Lake

Pelechuco lake is located in the Cordillera Apolobamba (Fig. 1) and, according to Kougkoulos et al. (2018), is considered a medium GLOF risk. This is due to the lake being in contact with steep (> 45°) surrounding slopes that could generate avalanches and/or rockfalls, which in turn could impact the lake and generate a displacement wave; this is the most common GLOF triggering mechanism in three different regions (Cordillera Blanca, North American Cordillera, Himalaya) (Emmer and Cochachin 2013). Further, the parent glacier is also in proximity (< 200 m) to the lake head, raising the possibility of ice calving into the lake, also generating a displacement wave.

2.1.2 Laguna Glaciar

Laguna Glaciar is located in the Cordillera Real (Fig. 1). According to Kougkoulos et al. (2018), this is considered a medium-risk lake due to a visibly low dam freeboard (< 5 m), as well as the lake being in contact with the retreating parent glacier, which could calve into the lake. The surrounding steep slopes (30–45°) also raise the possibility of avalanches and/or rockfalls impacting the lake.

2.1.3 Laguna Arkhata

Laguna Arkhata is located in the Cordillera Tres Cruces (Fig. 1). According to Kougkoulos et al. (2018), it is considered the highest risk lake. This is mostly due to the steepest slope (> 45°) surrounding the lake, capable of shedding avalanches and/or rockfalls into the lake, as well as the lake being in contact with the retreating parent glacier, which could calve into the lake. Specifically there are numerous steep, hanging areas of glacier ice above the lake.

2.2 Topographic data acquisition

Topographic data are central to the modelling of flood inundation. For each lake, we generated DEMs from stereo and tri-stereo SPOT 6/7 satellite imagery (1.5-m horizontal resolution) using the DEM extraction module in ENVI (version 5.3) (Table 2). For each of the four lakes and their GLOF runout zones, we sought to obtain at least two of the following types of image angles: one forward-looking (F), one nadir-looking (N), and one backward-looking (B) (Table 2). We acquired images with across-track angles of between − 15 and + 15 degrees. For each of the three lakes and potential GLOF runout zones, we identified approximately thirty tie points over the pairs of images used for each DEM in order to calculate shift parameters between images at each tie point, obtaining an overall root-mean-square error (RMSE) of less than 1 pixel (< 1.5 m). In areas where there is a lack of field GPS data, some studies suggest the use of Google Earth for obtaining ground control points (GCPs) (Watson et al. 2015). Therefore, we collected 15 GCPs for each set of images. The combination of FNB images produced a 1.5-m resolution DEM for each site. The DEMs were resampled to 2-m spatial resolution in order to eliminate artificial roughness due to the stereo processing technique (Kropáček et al. 2015).

Table 2 Satellite images used for DEM extraction

Sensor	Product	Satellite	Resolution (m)	Scene ID number	Date	Time	Incidence angle (across track)	Cloud cover (%)	Lake
				201308011418261		14:18:37	10.1	2.3	Arkhata
SPOT	TRI-STEREO	6	1.5	201308011419035	8/1/2015	14:19:14	6.1	1.4	
				201308011418447		14:18:56	7.4	1.5	
SPOT	MONO	6	1.5	201507091429124	7/9/2015	14:29:45	−11.2	1.1	Glaciar
SPOT	MONO	6	1.5	201304241430052	4/24/2015	14:30:27	−6.9	28.8	
SPOT	MONO	6	1.5	201306291422166	6/29/2013	14:22:33	16.0	0	Pelechuco, Keara
SPOT	MONO	6	1.5	201307111430521	7/11/2013	14:31:05	−14.9	3.2	
SPOT	MONO	7	1.5	201507291425516	7/29/2015	14:26:08	−0.5	7.6	

We also acquired an ASTER GDEM V2 with a 30-m horizontal resolution because, in Agua Blanca, a community situated downstream of Pelechuco lake, our SPOT-derived 2-m DEM contains a gap due to terrain shading. For this small area the ASTER GDEM was used instead. The ASTER GDEM has been used in several GLOF modelling studies (e.g. Gichamo et al. 2012; Wang et al. 2012; Watson et al. 2015) because it is free to download, and covers most of the Earth's landmass. In other cases, the DEM resolution has been resampled into a higher resolution in order to enable a higher level of precision in GLOF modelling, although the underlying DEM accuracy is not improved (e.g. Bajracharya et al. 2007; Allen et al. 2009; Rounce et al. 2016). In this study, we also applied a hydrological correction by filling sinks on both high (SPOT 2 m)- and low (ASTER GDEM 30 m)-resolution DEMs.

2.3 Estimating lake volume

Lake volume defines the maximum amount of water that could be involved in a GLOF. Since bathymetric data were unavailable for the lakes examined in this study, lake volume had to be estimated using lake area measured from satellite imagery and a mean depth based on empirical equations. Specifically, Cook and Quincey (2015) found that the relationship between lake area, depth and volume varied depending on the geomorphological context of the lake. Using the empirical data set compiled by Cook and Quincey (2015), the mean depth (Dm) of ice-dammed lakes (i.e. Keara in this study) is predicted by the equation:

$$Dm = 1 \times 10^{-5}A + 7.3051 \tag{1}$$

where A is lake area. This relationship yields an R^2 value of 0.90 and a P value <0.0001 (Appendix A1).

The mean depth of moraine-dammed lakes (i.e. Pelechuco and Laguna Glaciar in this study) is predicted by the equation:

$$Dm = 3 \times 10^{-5}A + 12.64 \tag{2}$$

This relationship yields an R^2 value of 0.83 and a P value <0.0001 (Appendix A1).

Laguna Arkhata is bedrock-dammed, but as yet there are no depth-area relationships that exist for such lakes. Therefore, lake depth for Laguna Arkhata was calculated using Eq. 2.

We calculated the errors on the constants within each of the two linear regression models in Eqs. 1 and 2 (at a confidence level of 95%) and applied those errors to determine a range of lake depths for the three lakes under investigation (Appendix A1, Table 1). Lake volume (V) was estimated by multiplying the measured lake area (in Google Earth Pro) by the derived lake depth from Eq. 1 or 2, and the errors associated with lake volume were estimated by propagating the errors associated with lake depth.

2.4 Estimating peak discharge

Several empirical equations have been applied in the past to estimate peak discharge from natural-dam (e.g. moraine, bedrock) failures (see Table 3 in Westoby et al. 2014a). These relationships require inputs such as lake area, lake volume, water depth at dam, dam height (e.g. Williams 1978; Froehlich 1995; Pierce et al. 2010). Some of these parameters can be

Table 3 Potential GLOF impact scenarios for all six villages under threat

Lake	Community	Coordinates (UTM)	Population[2]	Buildings[2]	Buildings affected[3]			Number of individuals per building	Population affected[3]		
					Optimistic	Intermediate	Pessimistic		Optimistic	Intermediate	Pessimistic
Pelechuco	Agua Blanca[1]	(19 L 488223 8361443)	379	164	48 (30)	53 (36)	161 (145)	2.31	111 (69)	122 (83)	372 (335)
	Pelechuco	(19 L 492374 8361658)	981	455	190 (120)	210 (135)	445 (433)	2.16	410 (259)	453 (291)	959 (934)
Laguna Glaciar	Sorata	(19 L 537548 8256109)	2788	1242	30 (8)	37 (10)	40 (40)	2.24	67 (18)	83 (22)	90 (90)
Laguna Arkhata	Totoral Pampa	(19 K 626722 8167167)	301	94	80 (70)	82 (75)	85 (80)	3.20	256 (224)	263 (240)	272 (256)
	Tres Rios	(19 K 628781 8167603)	303	173	150 (142)	170 (164)	173 (173)	1.75	263 (248)	298 (287)	303 (303)
	Khanuma	(19 K 631074 8167644)	223	81	12 (9)	15 (12)	75 (73)	2.75	33 (25)	41 (33)	206 (201)
All lakes	All communities		4975	2209	510 (379)	567 (432)	979 (944)		1140 (843)	1260 (956)	2202 (2119)

[1]For Agua Blanca, due to gaps on the 2-m DEM extraction we made use of ASTER 30-m GDEM to estimate potential impacts

[2]2015 data set from GeoBolivia, which refers to the 2012 population census from the Bolivian National Statistical Institute

[3]In parenthesis, > 2 m depth flood impacts on buildings and population

assessed remotely (e.g. from satellite imagery or DEMs), whereas others require field investigation. For simplicity, we chose to use two commonly employed relationships to model peak discharge from ice-dammed and moraine-dammed lakes. The equation of Walder and Costa (1996) for non-tunnel floods was used to model peak discharge ($Q_{\max}$) of the ice-dammed lake failure at Keara, which we used as a test case for our hydrodynamic modelling (see below).

$$Q_{\max} = 1100 \times \left(V/10^6\right)^{0.44} \tag{3}$$

The relationship of Evans (1986) was used for the potentially dangerous moraine-dammed lakes of Pelechuco and Laguna Glaciar, as well as the bedrock-dammed Laguna Arkhata:

$$Q_{\max} = 0.72\, V^{0.53} \tag{4}$$

All pro-glacial lake size estimations (e.g. area, depth, volume) can be found in Table 1.

2.5 Dam-breach hydrograph and modelling parameters

Numerous parameters (e.g. peak discharge, sediment load, channel roughness) can modify the flood inundation and flow behaviour of a simulated flood, leading to uncertainty in flood modelling and risk assessment (Anacona et al. 2015; Wang et al. 2015b; Kropáček et al. 2015). Table 1 presents a summary of the modelling scenarios undertaken, together with the accompanying values for each model parameter (i.e. lake volume, percentage of lake drainage, outburst duration, Manning's value, peak discharge). We discuss each of these parameters in turn.

We followed Fujita et al. (2013) in calculating potential flood volume (PFV) as the product of lake area and either the mean depth (*Dm*) or the potential lowering height (*Hp*); Fujita et al. (2013) recommend using the lower of these two values to calculate PFV. We compared our values for *Dm* (Sect. 2.3; Table 1) against those calculated for *Hp*. *Hp* is the amount of lake lowering expected during a GLOF assuming that, after GLOF initiation, incision into the moraine dam will proceed until the angle between the lake and the downstream area is lowered to 10° (termed the 'depression angle'). We created depression angle maps (Appendix A2) and mapped the steep lakefront area (SLA) 1-km downstream of each lake, following Fujita et al. (2013), in order to calculate *Hp* (see Appendix A2). In all cases, the value of *Dm* is lower than that calculated for *Hp*, and so *Dm* is used in the calculation of lake volume.

The volume of water drained from the lake is highly uncertain principally because this will be determined by the triggering mechanism, which could vary in nature and severity, and the resilience and integrity of the impounding dam. Hence, three different drainage volumes were modelled, which represent optimistic, intermediate, and pessimistic scenarios. Different values for the extent of lake drainage were defined, ranging from 20% of the lake volume for the optimistic scenario, 50% for intermediate, and 100% for the pessimistic scenario. These scenarios are guided by previous work on GLOF drainage volumes. For example, Anacona et al. (2014) studied 14 Patagonian moraine-dammed lakes before and after GLOF events and found that two lakes emptied entirely (100% drainage), four emptied by more than 50%, two by around 50%, and six lakes generated smaller outbursts with less than 20% drainage. In another study, Kropáček et al. (2015) modelled 125% lake drainage for their worst-case (pessimistic) scenario, with the additional 25% drainage accounting for possible future lake expansion in response to continued glacier recession. However, all lakes in our study are already at or very close to their maximum filling capacity, and so it is not necessary to model larger lakes. The lake drainage value for Keara was set to 100% since the observational evidence indicates that the lake drained completely (Hoffmann and Weggenmann 2013). For the other three lakes, we suggest that it is unlikely that they would drain completely, but we use the 100% drainage scenario as the worst possible case.

Previous studies have recommended a flood duration between 1000 and 2000s based on empirical data from the Swiss Alps (Haeberli 1983; Huggel et al. 2002). Therefore, we used 1000 s and 2000 s as outburst duration for the pessimistic and optimistic scenarios, respectively, and 1500 s for the intermediate scenario. As Worni et al. (2012) and Westoby et al. (2014a) suggest, if there are no data on lake outflow duration and lake discharge, the outflow hydrograph can only be validated indirectly (e.g. with the Keara event as a validation point in this case). Although simulations of drainage duration can be tuned to fit an observed hydrograph, hydrograph forecasting is difficult because non-linear flood physics make drainage duration sensitive to the initial conditions (Ng and Björnsson 2003), which are usually uncertain. All three of our potentially dangerous glacial lakes are either bedrock- or moraine-dammed, so we made the assumption that flood discharge would increase linearly to a peak, after which it decreases linearly to 0 m^3/s over a time span equal to that of the rising limb; in other words, hydrographs were assumed to be triangular in shape as has been applied in previous GLOF modelling studies (Anacona et al. 2015; Kropáček et al. 2015; Somos-Valenzuela et al. 2015; Wang et al. 2015b) (Fig. 2). Some previous studies have considered that the higher the peak discharge, the longer the flood duration (Anacona et al. 2015; Wang et al. 2015b), whereas others assume a shorter flood duration for a higher peak discharge (Somos-Valenzuela et al. 2015). We chose to use the latter option such that our worst-case pessimistic scenario has the highest peak discharge and shortest flood duration, and the optimistic scenario has the lowest peak discharge and longest flood duration. Ice-dammed lake failures usually generate flood hydrographs with a relatively slow, exponentially rising limb, and a rapidly falling limb (Kingslake 2013). Nevertheless, we chose to use

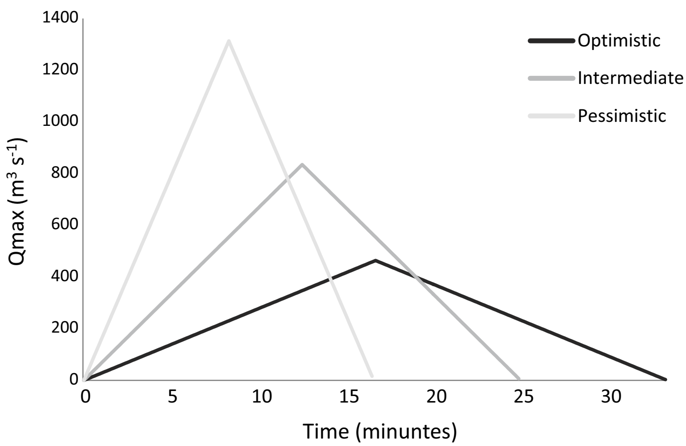

Fig. 2 Example breach hydrograph for Pelechuco lake illustrating all three scenarios for a potential GLOF (optimistic, intermediate, and pessimistic). The same hydrograph shapes are used for all three lakes

a triangular-shaped hydrograph for the Keara ice-dam breach because no detailed data were available concerning the event, and we can compare more readily with results from the three lakes that are yet to generate GLOFs.

In-channel and floodplain Manning's values for each scenario were set to represent mountain streams without vegetation (Table 1), although we could only verify the type of terrain by performing an inspection on Google Earth and from our own fieldwork observations at Pelechuco, in the Cordillera Apolobamba.

2.6 Hydrodynamic modelling of GLOFs

Modelling of GLOF hazard and risk has been undertaken in several regions around the world, using a variety of different approaches. Some studies have used simple geometric models such as the modified single flow (MSF) (Huggel et al. 2002; Allen et al. 2009; Prakash and Nagarajan 2017), the random walk process (Mergili and Schneider 2011), or the Monte Carlo Least Cost Path (MC-LCP) (Watson et al. 2015; Rounce et al. 2016, 2017) to make a rapid assessment of potential flood inundation. Such models require very little input data and can be applied to many lakes, but serve as a first-order assessment that cannot go as far as to produce realistic flood maps. Other studies have focused on more detailed modelling approaches using HEC-RAS 1D (Bajracharya et al. 2007; Dortch et al. 2011; Klimeš et al. 2014; Watson et al. 2015), HEC-RAS 2D (Anacona et al. 2015; Wang et al. 2015a, b), FLO 2D (Petrakov et al. 2012; Somos-Valenzuela et al. 2015), and BASEMENT (Worni et al. 2012, 2013; Somos-Valenzuela et al. 2016), all of which require further data such as channel bed roughness, and the volume of water that could drain from the lake. These techniques are capable of generating inundation maps (area affected, runout distance, and depth of flow) that can be used to inform risk management and mitigation strategies.

Here, GLOFs were modelled (inundation area, arrival time, depth, and velocity) using the 2D US Army Corp of Engineers model, HEC-RAS 5.0.3 (http://www.hec.usace.army.mil/). HEC-RAS was used because it is downloadable free of charge, and has been employed successfully to model GLOF inundation in a number of previous studies (e.g. Bajracharya et al. 2007; Dortch et al. 2011; Klimeš et al. 2014; Anacona et al. 2015; Wang et al. 2015a, b; Watson et al. 2015). The 2D version of this model can simulate multi-directional and multi-channel flows, which are characteristic of GLOFs (Westoby et al. 2014a, b; Wang et al. 2015b; Watson et al. 2015). The model set-up included the definition of upstream and downstream boundary conditions, the creation of a grid with elevation data, the selection of Manning's roughness values, slope parameters, and the model spatial domain. The unsteady flow simulation was performed for all four Bolivian GLOF case studies in order to observe: (1) peak flow propagation, (2) flood inundation extent, and (3) the flood water depth.

We used our simulated dam-breach hydrographs for the upstream boundary condition of each model (see Sect. 2.5 for more details). The normal depth option was used for the downstream boundary condition. This latter option uses Manning's equation to estimate a stage for each computed flow. To use this method, the user is required to enter a friction slope for the reach close to the boundary condition. If no detailed data exist, the slope of water surface can be used as a good estimate for the friction slope (Brunner 2010). This type of boundary condition should be placed far enough downstream of the study reach (i.e. potentially impacted communities) such that any errors it produces will not affect the results of the GLOF runout area (Brunner 2010; Watson et al. 2015). Hence, we placed the boundary 2-km downstream of the last community potentially affected by a GLOF from each lake. In addition, even though HEC-RAS has the ability to simulate debris flows, GLOFs were simulated as clear-water flows due to a lack of information about the nature of stream beds. We acknowledge that GLOFs are very likely to erode and entrain debris as they propagate downstream, and possibly evolve into debris flows, although many other studies also model GLOFs as clear-water flows due to data constraints (e.g. Anacona et al. 2015; Kropáček et al. 2015; Wang et al. 2015b; Watson et al. 2015).

Our overall approach was to test the model against field observations of the 2009 Keara event to ensure that realistic flood depths and inundation extent were achieved. The same modelling methodology was then applied to the three potentially dangerous lakes identified by Kougkoulos et al. (2018).

2.7 Population and infrastructure data

Population and infrastructure data are required to assess potential GLOF impacts. These data were acquired from the GeoBolivia portal (http://geo.gob.bo/portal/), which offers open access to the 2012 population census and infrastructure data of the Bolivian National Statistical Institute. To quantify the downstream impacts, we manually counted the number of buildings affected by the flood. For each community, we also divided the total population of the community by the number of buildings in the community to estimate the number of people per building. This enabled us to estimate the number of people impacted by the flood. However, we acknowledge that there are likely to be spatial differences in population within each community, and, because of seasonal migration within Bolivia (Oxfam 2009), there will be temporal population variations (which we have not considered further in this study).

Field observations in the Cordillera Apolobamba region in July 2015 demonstrate that building structures are usually single-storey residential dwellings made of unreinforced brick walls (Fig. 3). Roofs are mostly constructed from corrugated steel sheets. According to Reese et al. (2007), this type of structure is vulnerable to flood depths of greater than 2 m, and from observations of other types of extreme flood events, such as tsunamis, lahars, and debris flows, only the concrete floor is likely to remain intact after the passage of a $\geq$ 2 m flood (Reese et al. 2007). Hence, for each one of the three scenarios simulated for each lake, we estimate the impact on the downstream communities taking into account two inundation depths (1) the extent of the flood from the > 0 m flood depth and (2) the extent of the flood from the > 2 m flood depth.

3 Results

3.1 Modelling the 2009 Keara GLOF

The pre-GLOF lake area for Keara was 0.034 km^2, measured from an August 2005 satellite image in Google Earth. When multiplied with the lake depth (Eq. 1), the resulting lake volume is between 0.14×10^6 m^3 and 0.39×10^6 m^3, where the range in values accounts for potential errors in the relationship between depth, area, and volume (see Sect. 2.2) (Table 1). Figure 4 illustrates a simulation of the Keara event with the intermediate scenario (Table 1), as well as images taken shortly after the GLOF. Comparison of the incision and inundation displayed in the field photographs with the flow depths and inundation extents of the numerical model

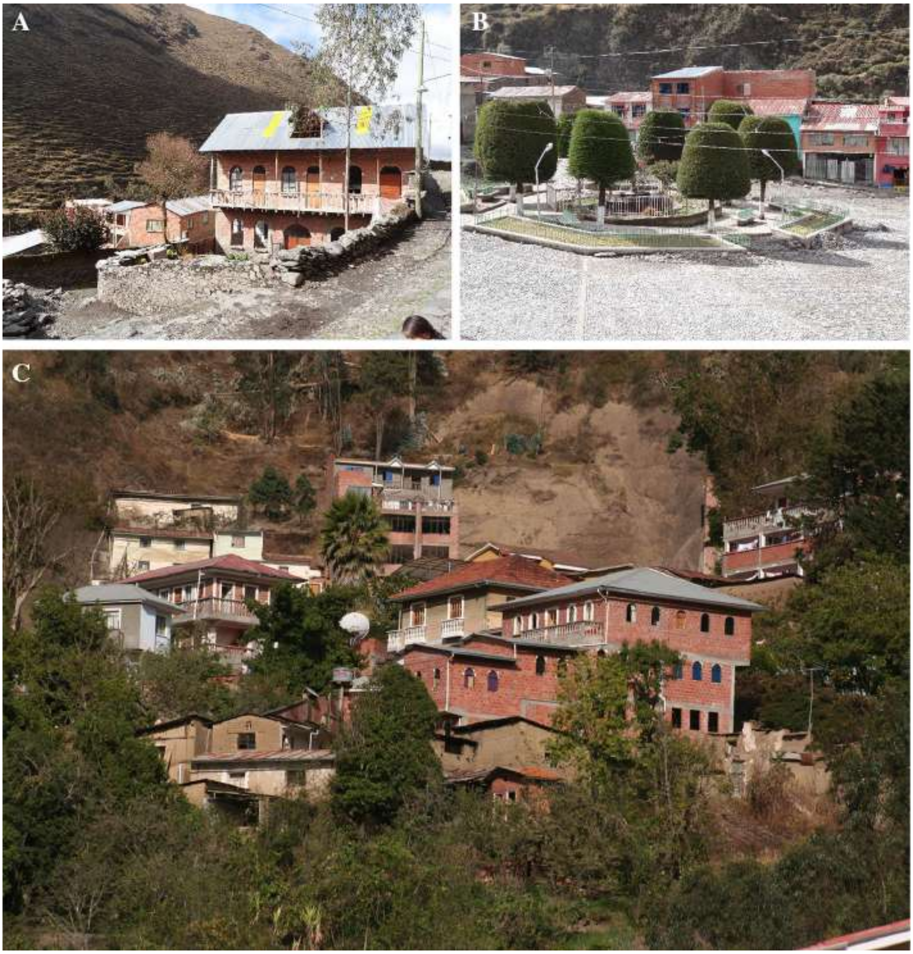

Fig. 3 Photographs illustrating typical brick structures with roofs made from corrugated steel sheets. Pelechuco (A and B), Sorata (C). Photograph credit: Dirk Hoffmann

shows good agreement. In location A, the flood depth was 4–6 mat the same location as the accompanying photograph, which shows a ~ 5-m-deep incision through proglacial till (Fig. 4). In location B, the model replicates flood inundation around farm buildings and walls with favourable comparison with the accompanying field photograph. In zone C (Figs. 4 and 5), we observe that infrastructure is only affected by flows that do not exceed 2 m, showing favourable comparison with the real event since no dwellings were destroyed during the GLOF.

3.2 Potential GLOF impacts from three dangerous lakes

3.2.1 Pelechuco lake

Two communities (Agua Blanca and Pelechuco) are situated downstream of Pelechuco Lake (Fig. 6). Agua Blanca is ~ 8.5 km from the lake and has a total population of 379

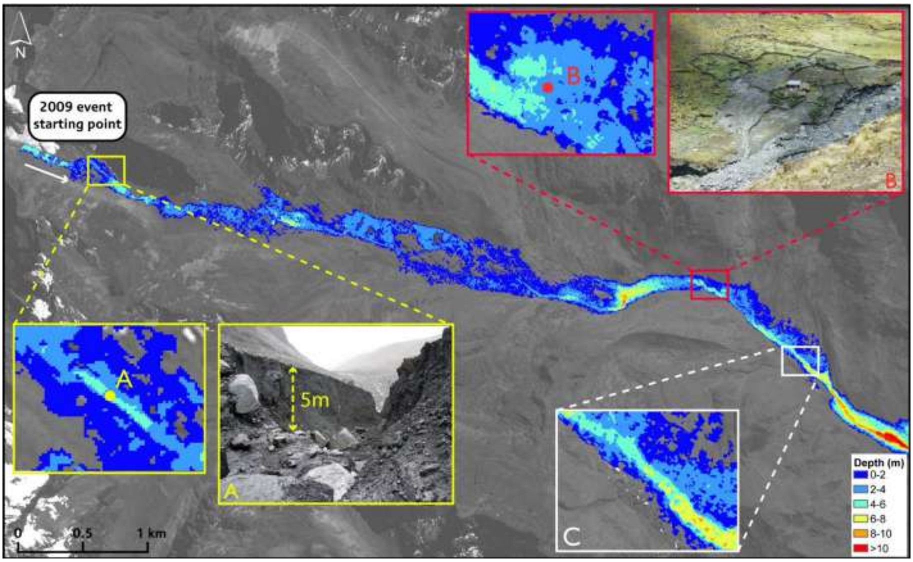

Fig. 4 Numerical simulation of the Keara November 2009 GLOF event. Zone A shows 4–6 m flow depths corresponding a ~ 5-m-deep incision through proglacial till illustrated in the field photograph. Zone B replicates flood inundation areal extent around farm buildings and walls with favourable comparison with the accompanying field photograph (note that the photograph is taken from a different orientation to the model run image). Zone C illustrates impacts on the Keara community. (A focused view is presented in Fig. 5.) The photographs were taken in the field on 3 November 2009, only hours after the event, by Martin Apaza Ticona, and used with his permission

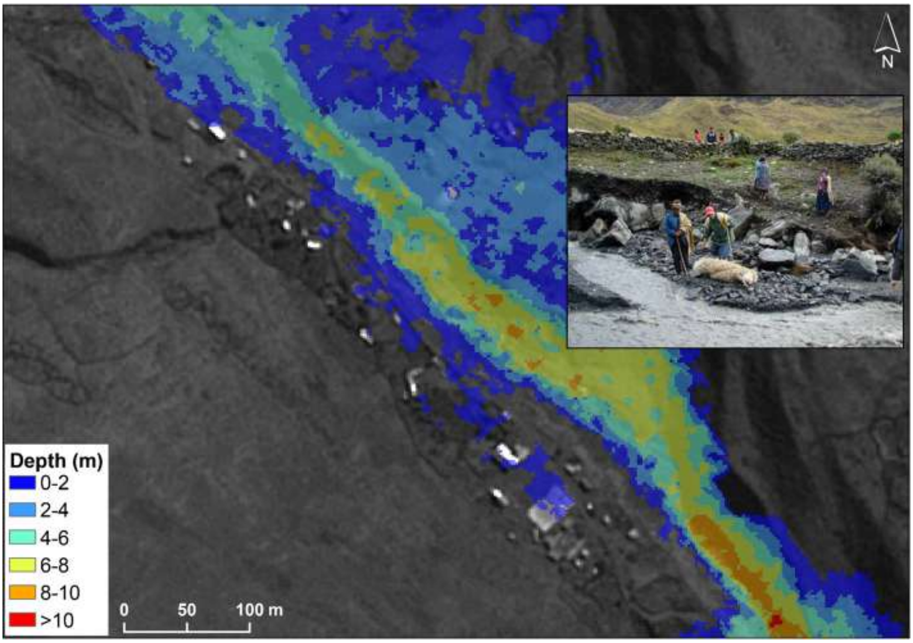

Fig. 5 Focused view of impacts on the Keara community. Photograph credit: Martin Apaza Ticona

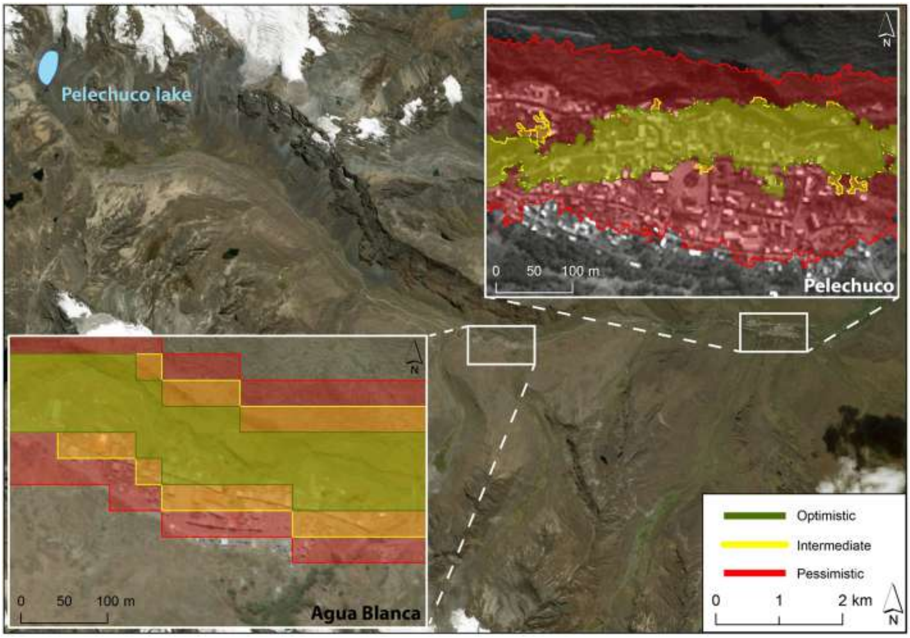

Fig. 6 Potential impacts for each modelled scenario for a GLOF (> 2 m flood depth) originating from Pelechuco lake. ASTER GDEM (30-m resolution) was used for Agua Blanca, because gaps created by shading on the 2-m SPOT extracted DEM made evaluation impossible. For Pelechuco, the 2-m DEM was used

individuals (Table 3). Agua Blanca is the only threatened community for which the ASTER GDEM is used in the hydraulic modelling because the SPOT-derived 2-m DEM contains a gap at this location due to terrain shading. Agua Blanca is also the smallest community (~ 30,600 m^2; Table 3), meaning that the 30-m ASTER GDEM offers a rather crude estimation of flood impact. Model results indicate that around 111 to 372 people could be affected by the flood, and between 69 and 335 of those people could be affected by potentially damaging flood waters of ≥ 2 m depth (Table 3). Damaging floods are considered here to be life-threatening events or events causing a significant damage to infrastructure. Figure 6 provides a visualisation of the inundated areas downstream of Pelechuco lake.

The village of Pelechuco is about three times larger than Agua Blanca in terms of population number (981 individuals) and sits ~ 12.5 km from the lake. The three scenarios show that between 410 and 959 individuals could be affected by a GLOF, and that between 259 and 934 people could be affected by damaging (≥ 2 m depth) floods (Table 3).

3.2.2 Laguna Glaciar

Laguna Glaciar is situated above the community of Sorata, which is home to ~ 2788 individuals and is also a popular hiking and climbing destination for tourists. The largest part of the community is situated between ~ 100 and 250 m above the meltwater channel and floodplain and so is largely safe from any immediate GLOF impacts. However, a small part of the town sits close to the channel. Our modelling reveals that between 67 and 90 people could

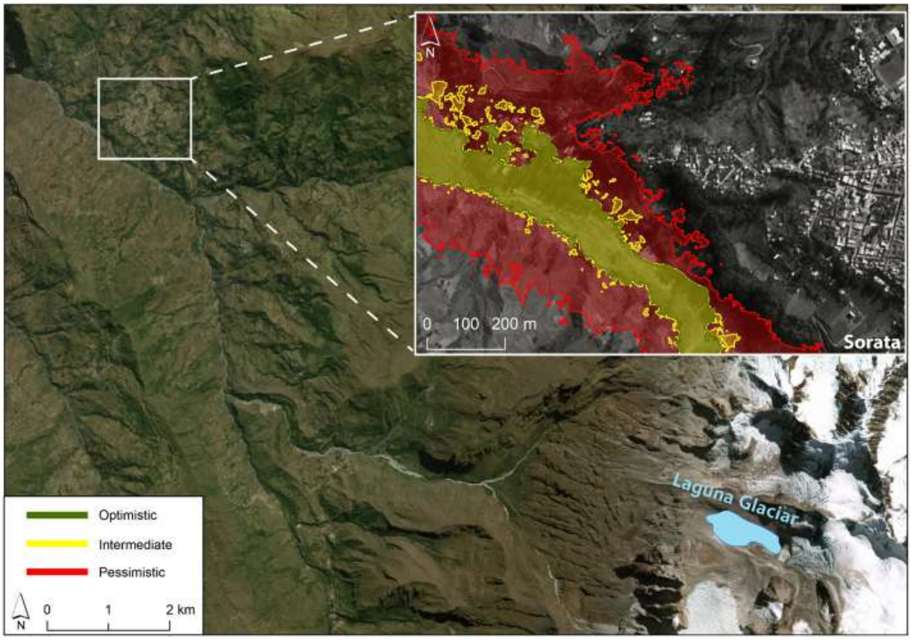

Fig. 7 Potential impacts for each modelled scenario for a GLOF (> 2 m flood depth) originating from Laguna Glaciar

be affected by the flood, and between 18 and 90 of those people could be affected by floods of ≥ 2 m depth (Table 3; Fig. 7).

3.2.3 Laguna Arkhata

Of all the glacial lakes in Bolivia, Kougkoulos et al. (2018) found that Laguna Arkhata represented the greatest risk to downstream communities. Totoral Pampa is the closest community to the lake (~ 6-km downstream) and is situated mostly within the floodplain of the meltwater stream that drains from the lake. Our modelling revealed that a GLOF could affect between 256 and 272 people (Table 3; Fig. 8). Therefore, even the optimistic scenario could affect most of the community.

Tres Rios, situated ~ 2-km downstream from Totoral Pampa, is located entirely on the floodplain. Thus, our modelling revealed that most of the community could be affected by a flood and 250 to 300 individuals could be exposed to potentially damaging floods.

Khanuma, which is situated another ~ 2-km downstream of Tres Rios, could be impacted to a lesser extent than the other two villages close to Laguna Arkhata. Modelling revealed that between 33 and 206 individuals could experience some flooding, and 25 and 201 of those people could be affected by damaging floods (Table 3; Fig. 8).

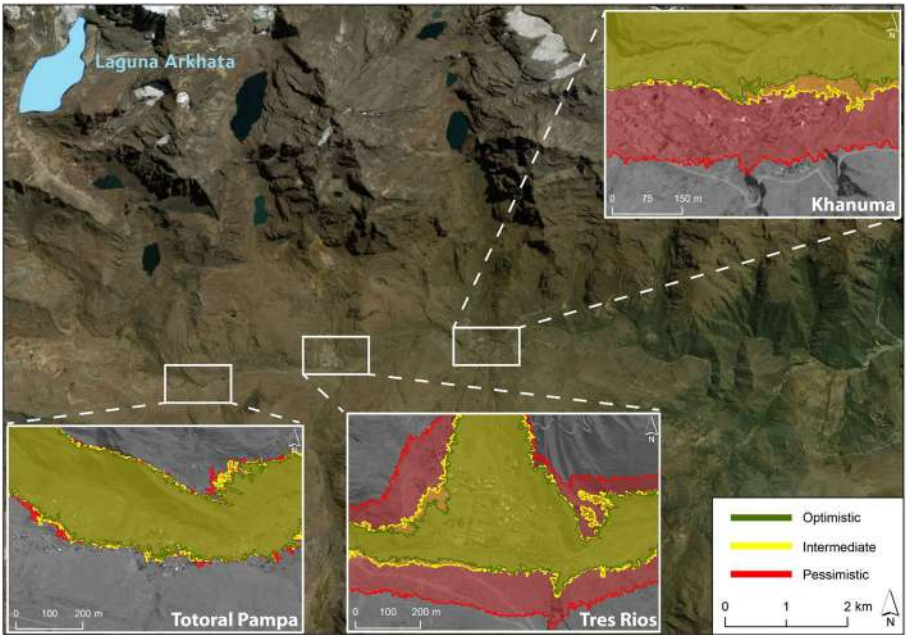

Fig. 8 Potential impacts for each modelled scenario for a GLOF (> 2 m flood depth) originating from Laguna Arkhata

4 Discussion

4.1 Modelling approach

For the first time, we have undertaken a hydrodynamic modelling study of GLOFs in the Bolivian Andes. For the most part, this assessment was achieved using a 2-m resolution DEM derived from SPOT 6/7 imagery as data input and HEC-RAS 5.0.3 to model clear-water flood flows. Our approach of producing and using a 2-m resolution DEM in favour of using coarser resolution, but freely available DEMs, such as ASTER GDEM or SRTM, offered us the best spatial resolution data set available to drive our model without having to resort to field-based topographic data acquisition through differential-GPS (d-GPS), LiDAR, or Structure-from-Motion (SfM) surveys. Coarser resolution DEMs have been used routinely in GLOF modelling (e.g. Anacona et al. 2015; Wang et al. 2015a), but our approach offers arguably more robust results for relatively narrow streams and valleys that may, in some parts of the reach, be on a scale at or below the spatial resolution of coarser DEMs. Hence, our 2-m DEMs offer a good balance between spatial resolution and convenience of data access, while maximising the veracity of numerical modelling output and facilitating a more robust risk assessment of downstream GLOF impacts.

We employed HEC-RAS 2D to model GLOFs because it is available free of charge, works directly in ArcMap, which is convenient, and has been used successfully in previous studies to model GLOF inundation (e.g. Bajracharya et al. 2007; Dortch et al. 2011; Klimeš et al. 2014; Anacona et al. 2015; Wang et al. 2015a, b; Watson et al. 2015). The 2D version of the model has a number of advantages over 1D models. Firstly, it offers the ability to simulate multi-directional and multi-channel flows (in contrast, 1D models are only capable of routing flow in one direction, i.e. downstream). Second, it models superelevation of flow around channel bends, hydraulic jumps (i.e. in-channel transitions between supercritical and subcritical flow regimes), and turbulent eddying (Westoby et al. 2014a). These conditions are characteristic of GLOFs, so it is advantageous to be able to model them effectively. Furthermore, with a 2D model, assessing people and properties at risk becomes a simpler task as there is no need to interpolate 1D results across the floodplain.

An issue for consideration was that we used HEC-RAS to model clear-water flows when it is likely that sediment will be entrained into the flow, changing its rheology, and thereby affecting its travel distance and downstream impacts. Westoby et al. (2014a) indicate that debris flows (with sediment comprising at least ~ 20% of flow volume) are more common than clear-water flows in GLOFs from moraine-dammed lakes. Furthermore, debris-laden flows will travel shorter distances than clear-water flows (Huggel et al. 2004). Therefore, in some cases they may not reach as far as our modelled clear-water flows, but will induce more damage to population and infrastructure situated in close proximity to the pro-glacial lakes (Reese et al. 2007; Jakob et al. 2012). Nonetheless, our study is not unusual in modelling GLOFs as clear-water flows (e.g. Anacona et al. 2015; Kropáček et al. 2015; Wang et al. 2015b; Watson et al. 2015). HEC-RAS 2D offers the possibility to include sediment entrainment in the unsteady flow simulations, which may improve the representativeness of the modelled floods. This would require field data on the sedimentary nature of potential flood channels and dams, which would be worthwhile obtaining in future studies. Given these uncertainties, we tested the robustness of our modelling approach against field data following the ice-dammed lake outburst at Keara, in the Apolobamba region (Figs. 1, 4). Comparison of our modelled flood inundation and flow depth results with documentary evidence of GLOF impacts illustrates that the model produced realistic results (Figs. 4, 5).

A limitation of the HEC-RAS model is that, although it can model sediment entrainment, it cannot model debris flows that may result from a GLOF (Wang et al. 2015a, b). Unfortunately, cost constraints and a lack of field data on channel and moraines sediments did not permit the use of models such as RAMMS, which have been used in previous studies to model GLOFs and debris flows originating from such events (e.g. Frey et al. 2016). Other options that have been used to model GLOFs include FLO-2D (e.g. Somos-Valenzuela et al. 2016), the PRO version of which comes at a cost, but which can be used to model debris flows, and BASEMENT (e.g. Worni et al. 2012, 2013; Lala et al. 2017), which is downloadable free of charge, but cannot model debris flows. A direct comparison of the outputs of each of these modelling tools is beyond the scope of this study, but it would be worthwhile undertaking such work in the future for the three lakes investigated here. Further, recent GLOF studies have attempted to model complex process chains in a multi-hazard proglacial lake context (e.g. Lala et al. 2017; Mergili et al. 2018), and it is suggested here that investigation of process chains for GLOFs from proglacial lakes in Bolivia would be a valuable undertaking in the future.

Some uncertainties in our modelling include the volume of the lakes, the appropriate Manning's value to use for the channel, and the population living within each community. Hence, a field study of lake bathymetries, the nature of stream sediments, and a survey of the number of community occupants, which may change seasonally, would be welcome.

4.2 GLOF impacts and risk management

Kougkoulos et al. (2018) identified three glacial lakes across Bolivia that represent medium and high GLOF risk. Table 3 provides a summary of the potential impacts of GLOFs from those three lakes, and Figs. 6, 7, and 8 give a visualisation of flood inundation for each affected community. In total, there are six communities at risk, which are home to ~4975 people and 2209 buildings. Our modelling results indicate that between 1140 and 2202 people could be affected by GLOF events if all three lakes burst and between 843 and 2119 of those people could be impacted by potentially damaging floods where the flow depth is modelled to be ≥ 2 m. Figure 9 provides a summary and comparison of GLOF impacts across the study sites.

4.2.1 Pelechuco Lake

Our results indicate that Pelechuco lake should be a priority for risk mitigation efforts. Kougkoulos et al. (2018) ranked this lake as 'medium' risk, and the modelling results presented in the current study show that part of both downstream communities (Agua Blanca and Pelechuco) could be severely damaged by potential flooding. Pelechuco in particular stands out on Fig. 9 as having the greatest number of potentially impacted people across all three lakes investigated. This is despite the fact that Pelechuco lake is the smallest of the three lakes examined here, and hence generates the smallest floods (Table 3). The high number of potentially impacted people results from the high proportion of the village area that is situated along the riverbanks (Fig. 6). The impact of a flood from Pelechuco lake on the community of Agua Blanca may require further detailed field investigation because only the 30-m resolution ASTER GDEM was available to drive the HEC-RAS model at this section of the channel reach (Fig. 6).

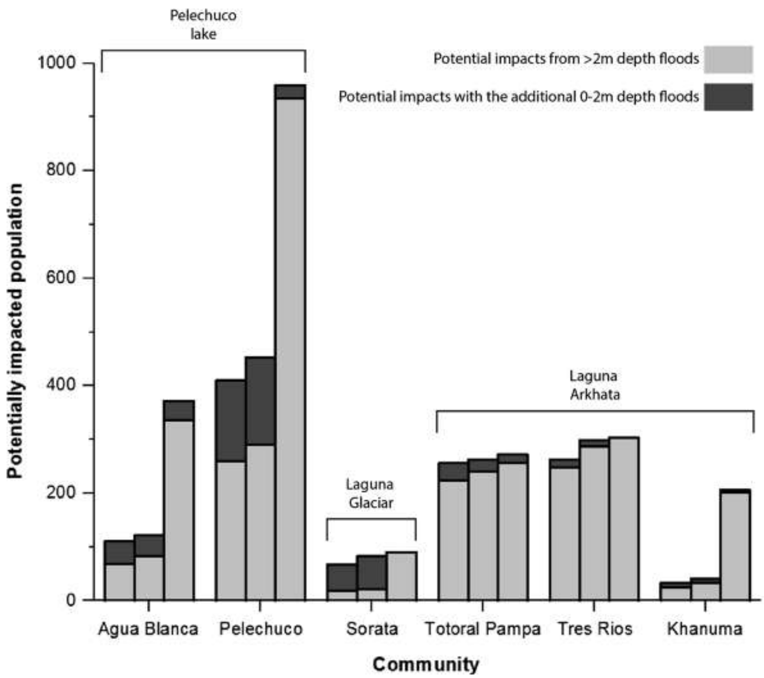

Fig. 9 Potentially affected population numbers per community and per modelled scenario. Left (optimistic), centre (intermediate), right (pessimistic)

4.2.2 Laguna Glaciar

Of the three lakes, Laguna Glaciar arguably represents the lowest priority for risk managers in Bolivia. Kougkoulos et al. (2018) ranked the lake as medium risk, and our results indicate that, because a large part of the community of Sorata is situated far from the floodplain, the impacts of a GLOF would be relatively low (Figs. 7, 9). Cost–benefit analysis between relocation of the part of the community potentially hit by a flood, and a combination of sustaining GLOF awareness programmes and early warning systems could be worthwhile undertaking for local risk managers and stakeholders. Ongoing monitoring of the lake and its surroundings as the glacier continues to recede would certainly be valuable.

4.2.3 Laguna Arkhata

Laguna Arkhata is a bedrock-dammed lake, and hence the probability of the dam failing and the lake draining completely is low; the most likely scenario would be an ice, snow, or rock avalanche impacting the lake and generating a wave that overtops the bedrock dam. However, irrespective of the drainage scenario (optimistic to pessimistic), the numbers of people affected by GLOFs vary relatively little for Totoral Pampa and Tres Rios; the differences are more marked for Khanuma. All three communities are affected by floods because they are located on floodplains. The communities of Totoral Pampa and Tres Rios look particularly vulnerable to GLOFs Totoral Pampa would be the first to be hit by a GLOF, and no matter what scenario is used in the modelling (from pessimistic to optimistic), Tres Rios is almost completely inundated from all flood scenarios because of its position on a floodplain (Figs. 8, 9). This provokes the question of whether any structural or non-structural measures could be applied in these communities (e.g. GLOF awareness programmes, flood defence construction, community relocation). Future studies could focus on analysing the benefit of a managed retreat, by basically relocating most of the community outside the risky areas which is an increasingly discussed technique in the context of climate change for numerous regions facing various types of natural hazards around the world (Hino et al. 2017).

5 Conclusion

For the first time, we have modelled potential glacial lake outburst floods (GLOFs) in the Bolivian Andes. This was achieved using high-resolution (2 m per pixel) DEMs derived from (tri-) stereo SPOT satellite imagery to drive a 2D hydrodynamic model (HEC-RAS 5.0.3). The modelling approach was first tested against field evidence from a documented GLOF event at Keara in the Apolobamba region in 2009 and was shown to reproduce realistic flood depths and inundations. The model was then applied to three lakes that have been identified previously as representing a GLOF risk to downstream communities (Kougkoulos et al. 2018). These are Pelechuco lake, in the Apolobamba region, and Laguna Glaciar and Laguna Arkhata, in the Cordillera Real. GLOFs from all three lakes were shown to represent potentially life-threatening and/or damaging events. In total, GLOFs from the three lakes could impact six downstream communities. As a sensitivity analysis, we ran our model for three scenarios, representing pessimistic, intermediate, and optimistic scenarios, by varying model parameterisation. These scenarios give a range in the number of impacted people. In total, between 1140 and 2202 people could be affected by flooding if all lakes were to burst, and between 843 and 2119 of those people could be exposed to damaging floods (flow depth ≥ 2 m). Laguna Arkhata and Pelechuco lake represent the greatest GLOF risk due to the large numbers of people who live in the potential flow paths, and hence should be a priority for risk managers.

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References

Allen SK, Schneider D, Owens IF (2009) First approaches towards modelling glacial hazards in the Mount Cook region of New Zealand's Southern Alps. Nat Hazards Earth Syst Sci 9:481–499. https://doi.org/10.5194/nhess-9-481-2009

Anacona P, Norton KP, Mackintosh A (2014) Moraine-dammed lake failures in Patagonia and assessment of outburst susceptibility in the Baker Basin. Nat Hazards Earth Syst Sci 14:3243–3259. https://doi.org/10.5194/nhess-14-3243-2014

Anacona PI, Mackintosh A, Norton K (2015) Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia: lessons for GLOF risk management. Sci Total Environ 527–528:1–11. https://doi.org/10.1016/j.scitotenv.2015.04.096

Bajracharya B, Shrestha AB, Rajbhandari L (2007) Glacial Lake Outburst Floods in the Sagarmatha Region. Mt Res Dev 27:336–344. https://doi.org/10.1659/mrd.0783

Brunner GW (2010) HEC-RAS River Analysis System User's Manual. US Army Corps of Engineers, California. http://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS_4.1_Users_Manual.pdf. Accessed 01 Nov 2017

Carrivick JL, Tweed FS (2013) Proglacial Lakes: character, behaviour and geological importance. Quat Sci Rev 78:34–52. https://doi.org/10.1016/j.quascirev.2013.07.028

Carrivick JL, Tweed FS (2016) A global assessment of the societal impacts of glacier outburst floods. Glob Planet Change 144:1–16. https://doi.org/10.1016/j.gloplacha.2016.07.001

Cook SJ, Quincey DJ (2015) Estimating the volume of Alpine glacial lakes. Earth Surf Dyn 3:559–575. https://doi.org/10.5194/esurf-3-559-2015

Cook SJ, Swift DA (2012) Subglacial basins: their origin and importance in glacial systems and landscapes. Earth-Science Rev 115:332–372. https://doi.org/10.1016/j.earscirev.2012.09.009

Cook SJ, Kougkoulos I, Edwards LA, Dortch J, Hoffmann D (2016) Glacier change and glacial lake outburst flood risk in the Bolivian Andes. Cryosph 10:2399–2413. https://doi.org/10.5194/tc-10-2399-2016

Dortch JM, Owen LA, Caffee MW, Kamp U (2011) Catastrophic partial drainage of Pangong Tso, northern India and Tibet. Geomorphology 125:109–121. https://doi.org/10.1016/j.geomorph.2010.08.017

Emmer A, Cochachin A (2013) The causes and mechanisms of moraine-dammed lake failures in the cordillera blanca, North American Cordillera, and Himalayas. Acta Univ Carolinae, Geogr 48:5–15

Emmer A, Vilímek V, Huggel C, Klimeš J, Schaub Y (2016) Limits and challenges to compiling and developing a database of glacial lake outburst floods. Landslides. https://doi.org/10.1007/s10346-016-0686-6

Evans SG (1986) The maximum discharge of outburst floods caused by the breaching of man-made and natural dams. Can Geotech J 23:385–387. https://doi.org/10.1139/t86-053

Frey H, Huggel C, Bühler Y, Buis D, Burga MD, Choquevilca W, Fernandez F, García Hernández J, Giráldez C, Loarte E, Masias P, Portocarrero C, Vicuña L, Walser M (2016) A robust debris-flow and

GLOF risk management strategy for a data-scarce catchment in Santa Teresa, Peru. Landslides. https://doi.org/10.1007/s10346-015-0669-z
Froehlich DC (1995) Peak outflow from breached embankment dam. J Water Resour 121:90–97. https://doi.org/10.1061/(ASCE)0733-9496(1995)121:1(90)
Fujita K, Sakai A, Takenaka S et al (2013) Potential flood volume of Himalayan glacial lakes. Nat Hazards Earth Syst Sci 13:1827–1839. https://doi.org/10.5194/nhess-13-1827-2013
Gichamo TZ, Popescu I, Jonoski A, Solomatine D (2012) River cross-section extraction from the ASTER global DEM for flood modeling. Environ Model Softw 31:37–46. https://doi.org/10.1016/j.envsoft.2011.12.003
Haeberli W (1983) Frequency characteristics of glacier floods in The Swiss Alps. Ann Glaciol 4:85–90
Hanshaw MN, Bookhagen B (2014) Glacial areas, lake areas, and snow lines from 1975 to 2012: status of the cordillera vilcanota, including the Quelccaya Ice Cap, northern central Andes, Peru. Cryosphere 8:359–376. https://doi.org/10.5194/tc-8-359-2014
Hino M, Field CB, Mach KJ (2017) Managed retreat as a response to natural hazard risk. Nat Clim Chang 7:364–370. https://doi.org/10.1038/nclimate3252
Hoffmann D, Weggenmann D (2013) Climate change induced glacier retreat and risk management: glacial lake outburst floods (GLOFs) in the Apolobamba mountain range, Bolivia. Chang Disaster Risk Manag. https://doi.org/10.1007/978-3-642-31110-9_5
Huggel C, Kääb A, Haeberli W, Teysseire P, Paul F (2002) Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can Geotech J 39:316–330. https://doi.org/10.1139/t01-099
Huggel C, Haeberli W, Kääb A, Bieri D, Richardson S (2004) An assessment procedure for glacial hazards in the Swiss Alps. Can Geotech J 41:1068–1083. https://doi.org/10.1139/t04-053
Jakob M, Stein D, Ulmi M (2012) Vulnerability of buildings to debris flow impact. Nat Hazards 60:241–261. https://doi.org/10.1007/s11069-011-0007-2
Kingslake J (2013) Modelling ice-dammed lake drainage
Klimeš J, Benešová M, Vilímek V, Bouška P, Cochachin Rapre A (2014) The reconstruction of a glacial lake outburst flood using HEC-RAS and its significance for future hazard assessments: an example from Lake 513 in the Cordillera Blanca, Peru. Nat Hazards 71:1617–1638. https://doi.org/10.1007/s11069-013-0968-4
Komori J (2008) Recent expansions of glacial lakes in the Bhutan Himalayas. Quat Int 184:177–186. https://doi.org/10.1016/j.quaint.2007.09.012
Kougkoulos I, Cook SJ, Jomelli V, Clarke L, Symeonakis E, Dortch JM, Edwards LA, Merad M (2018) Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2017.10.083
Kropáček J, Neckel N, Tyrna B, Holzer N, Hovden A, Gourmelen N, Schneider C, Buchroithner M, Hochschild V (2015) Repeated glacial lake outburst flood threatening the oldest Buddhist monastery in north-western Nepal. Nat Hazards Earth Syst Sci 15:2425–2437. https://doi.org/10.5194/nhess-15-2425-2015
Lala JM, Rounce DR, Mckinney DC (2017) Modeling the glacial lake outburst flood process chain in the Nepal Himalaya: reassessing Imja Tsho's hazard. Hydrol Earth Syst Sci Discuss. https://doi.org/10.5194/hess-2017-683
López-Moreno JI, Fontaneda S, Bazo J, Revuelto J, Azorin-Molina C, Valero-Garcés B, Morán-Tejeda E, Vicente-Serrano SM, Zubieta R, Alejo-Cochachín J (2014) Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru. Glob Planet Change 112:1–11. https://doi.org/10.1016/j.gloplacha.2013.10.010
Mergili M, Schneider JF (2011) Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. Nat Hazards Earth Syst Sci 11:1447–1462. https://doi.org/10.5194/nhess-11-1447-2011
Mergili M, Emmer A, Juřicová A et al (2018) How well can we simulate complex hydro-geomorphic process chains? The 2012 multi-lake outburst flood in the Santa Cruz Valley (Cordillera Blanca, Perú). Earth Surf Process Landforms. https://doi.org/10.1002/esp.4318
Ng F, Björnsson H (2003) On the Clague-Mathews relation for Jökulhlaups. J Glaciol 49:161–172. https://doi.org/10.3189/172756503781830836
Oxfam International Report (2009) Climate change, poverty and adaptation
Petrakov DA, Tutubalina OV, Aleinikov AA et al (2012) Monitoring of Bashkara Glacier lakes (Central Caucasus, Russia) and modelling of their potential outburst. Nat Hazards 61:1293–1316. https://doi.org/10.1007/s11069-011-9983-5
Pierce MW, Thornton CI, Abt SR (2010) Predicting peak outflow from breached embankment dams. J Hydrol Eng 15:338–349

Prakash C, Nagarajan R (2017) Outburst susceptibility assessment of moraine-dammed lakes in Western Himalaya using an analytic hierarchy process. Earth Surf Process Landforms 42:2306–2321. https://doi.org/10.1002/esp.4185
Reese S, Cousins WJ, Power WL et al (2007) Tsunami vulnerability of buildings and people in South Java—field observations after the July 2006 Java tsunami. Nat Hazards Earth Syst Sci 7:573–589. https://doi.org/10.5194/nhess-7-573-2007
Richardson SD, Reynolds JM (2000) An overview of glacial hazards in the Himalayas. Quat Int 65–66:31–47. https://doi.org/10.1016/S1040-6182(99)00035-X
Rounce DR, McKinney DC, Lala JM et al (2016) A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. Hydrol Earth Syst Sci 20:3455–3475. https://doi.org/10.5194/hess-20-3455-2016
Rounce DR, Watson CS, McKinney DC (2017) Identification of Hazard and Risk for Glacial Lakes in the Nepal Himalaya Using Satellite Imagery from 2000–2015. Remote Sens 9:654. https://doi.org/10.3390/rs9070654
Somos-Valenzuela MA, McKinney DC, Byers AC, Rounce DR, Portocarrero C, Lamsal D (2015) Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal. Hydrol Earth Syst Sci 19:1401–1412. https://doi.org/10.5194/hess-19-1401-2015
Somos-Valenzuela MA, Chisolm RE, Rivas DS, Portocarrero C, McKinney DC (2016) Modeling glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru. Hydrol Earth Syst Sci Discuss 2010:1–61. https://doi.org/10.5194/hess-2015-512
Vilímek V, Emmer A, Huggel C, Schaub Y, Würmli S (2013) Database of glacial lake outburst floods (GLOFs)-IPL project No. 179. Landslides 11:161–165. https://doi.org/10.1007/s10346-013-0448-7
Walder JS, Costa JE (1996) Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. Earth Surf Process Landforms 21:701–723
Wang W, Yang X, Yao T (2012) Evaluation of ASTER GDEM and SRTM and their suitability in hydraulic modelling of a glacial lake outburst flood in southeast Tibet. Hydrol Process 26:213–225. https://doi.org/10.1002/hyp.8127
Wang S, Qin D, Xiao C (2015a) Moraine-dammed lake distribution and outburst flood risk in the Chinese Himalaya. J Glaciol 61:115–126. https://doi.org/10.3189/2015JoG14J097
Wang W, Gao Y, Iribarren Anacona P, Lei Y, Xiang Y, Zhang G, Li S, Lu A (2015b) Integrated hazard assessment of Cirenmaco glacial lake in Zhangzangbo valley, Central Himalayas. Geomorphology. https://doi.org/10.1016/j.geomorph.2015.08.013
Watson CS, Carrivick J, Quincey D (2015) An improved method to represent DEM uncertainty in glacial lake outburst flood propagation using stochastic simulations. J Hydrol 529:1373–1389. https://doi.org/10.1016/j.jhydrol.2015.08.046
Westoby MJ, Glasser NF, Brasington J, Hambrey MJ, Quincey DJ, Reynolds JM (2014a) Modelling outburst floods from moraine-dammed glacial lakes. Earth-Sci Rev 134:137–159. https://doi.org/10.1016/j.earscirev.2014.03.009
Westoby MJ, Glasser NF, Hambrey MJ, Brasington J, Reynolds JM, Hassan MAAM (2014b) Reconstructing historic glacial lakeoutburst floods through numerical modelling and geomorphological assessment: extreme events in the himalaya. Earth Surf Process Landforms 39:1675–1692. https://doi.org/10.1002/esp.3617
Williams GP (1978) Bank-full discharge of rivers. Water Resources Res 14:1141–1154. https://doi.org/10.1029/WR014i006p01141
Worni R, Stoffel M, Huggel C, Volz C, Casteller A, Luckman B (2012) Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). J Hydrol 444–445:134–145. https://doi.org/10.1016/j.jhydrol.2012.04.013
Worni R, Huggel C, Stoffel M (2013) Glacial lakes in the Indian Himalayas–from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. Sci Total Environ 468–469:S71–S84. https://doi.org/10.1016/j.scitotenv.2012.11.043
Zemp M, Frey H, Gärtner-Roer I, Nussbaumer SU, Hoelzle M, Paul F, Haeberli W, Denzinger F, Ahlstrøm AP, Anderson B, Bajracharya S, Baroni C, Braun LN, Càceres BE, Casassa G, Cobos G, Dàvila LR, Delgado Granados H, Demuth MN, Espizua L, Fischer A, Fujita K, Gadek B, Ghazanfar A, Hagen JO, Holmlund P, Karimi N, Li Z, Pelto M, Pitte P, Popovnin VV, Portocarrero CA, Prinz R, Sangewar CV, Severskiy I, Sigurdsson O, Soruco A, Usubaliev R, Vincent C (2015) Historically unprecedented global glacier decline in the early 21st century. J Glaciol 61:745–762. https://doi.org/10.3189/2015JoG15J017

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Appendix 3.1. Glacier area tables (km^2). Top: Glacier areas per year and per Cordillera; Middle: Glacier areas per year and per Cordillera with range divide; Bottom: Glacier areas per year and per Cordillera with altitude divide.

Year	Apolobamba	Real	Tres Cruzes	Total
1986	172	315	42	529
1992	148	261	34	442
1999	133	242	31	407
2005	123	211	29	363
2010	101	191	25	317
2014	96	183	22	301
2018	89	170	22	281

Year	Apolobamba		Real		Tres Cruzes		Total	
	West	East	West	East	West	East	West	East
1986	67	104	179	136	24	17	270	257
1992	58	89	167	93	18	14	243	196
1999	51	81	151	91	19	12	221	184
2005	48	74	137	73	18	10	203	157
2010	42	59	107	82	16	8	165	149
2014	38	57	105	77	15	6	158	140
2018	36	51	101	69	14	7	151	127

Cordillera	Altitude (m)	1986	1992	1999	2005	2010	2014	2018
	<5000	23	17	10	9	4	2	2
Apolobamba	5000-5500	131	114	107	98	82	78	73
	>5500	18	17	15	15	14	15	13
	<5000	28	22	16	10	9	7	5
Real	5000-5500	208	170	161	136	120	115	106
	>5500	79	69	65	65	62	61	59
	<5000	1	0	0	0	0	0	0
Tres Cruzes	5000-5500	37	30	28	26	22	20	20
	>5500	3	3	3	2	2	1	1
	<5000	52	39	26	19	13	9	7
Total	5000-5500	376	314	296	260	224	213	199
	>5500	100	89	83	82	78	77	73

Appendix 4.1. Criteria description and threshold definition

Triggers

Regional seismic activity (TR.1)

Regional seismic activity has been recognised by many authors as a key trigger of dam collapse, as well as generation of rockfalls, landslides, snow avalanches and icefalls (Zapata, 2000; Mergili and Schneider, 2011; Emmer and Vilimek, 2013; Rounce et al., 2016). One of the clearest global measures is the maximum possible Peak Ground Acceleration PGAmax (m s^{-2}) which can be obtained for a global scale from the Global Seismic Hazard Map (http://gmo.gfz-potsdam.de). The thresholds set by Mergili and Schneider (2011) are divided into low (<0.5 m/s^2) and high (>0.5 m/s^2) seismic hazard. Since our criteria are divided into three classes, and we aim to capture seismic hazard for any situation globally, we decided to also use the upper threshold set by Shi and Kasperson (2015), and therefore we extended the high-risk category to 3.9 m/s^2 and added the medium-risk class.

Intense precipitation events (TR.2) and high temperature events (TR.3)

Intense precipitation events and high temperature events have been combined in previous studies as the 'hydrometeorological' situation (Huggel et al., 2004; Wang et al., 2011), and such events have the capacity to trigger mass movements into a lake. Nevertheless, this does not offer the possibility to score each element of the criterion individually, indicating non-exhaustiveness. After splitting them into two separate criteria, the use of two global BIOCLIM indicators (BIO 4 - temperature seasonality; BIO 15 - precipitation seasonality) were considered as the most appropriate surrogates. Our rationale was that a more varied seasonal cycle in precipitation or temperature would be a reasonable proxy for how intense the precipitation or temperature events are. Precipitation seasonality is the measure of the variation in monthly precipitation totals over the course of the year. This index is the ratio of the standard deviation of the monthly total precipitation to the mean monthly total precipitation (also known as the coefficient of variation) and is expressed as a percentage; larger percentages represent greater variability of precipitation. We divided the three classes into <50% (low risk), which represents precipitation occurring roughly equally throughout the year, 50-100% (medium risk) representing seasonal precipitation, and >100% (high risk) which indicates precipitation occurring in less than three months in the year. Temperature seasonality indicates the amount of temperature variation over a given year (or averaged years) based on the standard deviation (variation) of monthly temperature averages. It is a measure of temperature change over the course of the year. The larger the standard deviation, the greater the variability of temperature. We have divided into three classes: <50%

(low risk), 50-100% (medium risk), >100% (high risk). For extra information on these variables visit: https://pubs.usgs.gov/ds/691/ds691.pdf

Mechanisms

Dam freeboard (ME.1)

Dam freeboard is one of the most commonly used factors to determine the possibility of a wave overtopping any type of dam. Nevertheless, the exact height of the freeboard is difficult to measure from satellite data (Worni et al., 2013). We set the thresholds here to low (>15 m), medium (15-5 m) and high risk (<5 m) according to previous studies that have evaluated freeboard from open-source, high-resolution satellite imagery (Wang et al., 2012; Worni et al., 2013).

Dam type (ME.2)

Lake dam type has been considered as one of the main factors for outburst probability (Huggel et al., 2004; Mergili and Schneider, 2011; Emmer and Vilímek, 2013). Carrivick and Tweed (2016) observed that, in terms of historical and modern glacier floods occurring worldwide, 70 % are from ice-dammed lakes, 9 % are from moraine-dammed lakes, 16 % are from an unknown dam type/trigger, and 3 % are triggered by volcanic activity (nearly all of them taking place in Iceland). In another study, Emmer et al. (2016b) summarized more than 500 GLOF events based on scientific research articles, non-scientific reports and regional studies. They identified 380 GLOFs from ice-dammed lakes, 130 GLOFs from moraine-dammed lakes and several GLOFs originating from bedrock-dammed lakes or lakes with combined dam. Even though moraine dammed lakes have been deadlier than ice-dammed lakes (e.g. Lake Palcacocha in 1941), the potential loss of human life remains a separate criterion and we only examine here the stability of the dam (to avoid double-counting criteria). Hence, there are three classes: ice-dam (high risk), moraine-dam (medium risk), and bedrock dam (low risk) which are also used in previous studies (Huggel et al., 2004; Worni et al., 2013; Wang et al., 2013).

Steepest slope surrounding lake (ME.3)

Mass movements entering a glacial lake are the main cause leading to GLOFs (Worni et al., 2013; Rounce et al., 2016). Steep slopes promote mass movements, which in turn can impact the lake and generate a flood wave that overtops or destroys the natural dam. Areas with a slope greater than 30° are susceptible to rock avalanches or landslides (Alean, 1985; Bolch et al., 2011; Rounce et al., 2016). Moreover, according to Alean (1985), temperate glaciers have been found to produce ice avalanches from a minimum slope of 25°, and cold-based glaciers from 45°. Therefore, we decided to consider 25° as the minimum threshold slope that can generate mass movements into a lake. Any lake that is not surrounded by a slope of at least 25° is not considered in the study. In addition, previous studies have considered only lakes within 500m of a glacier to be potential GLOF sources (e.g. Wang et al., 2011, 2015). Therefore, lakes that are further than 500m from a slope, or closer than 500m from a < 25° slope are not considered in this study. We defined three classes: <30° slope (low risk), 30-45° slope (medium risk) and >45° slope (high risk). The high-risk threshold is lowered to 30° for the sensitivity analysis in order to observe potential differences and risk class changes for the studied lakes.

Distance between lake and steepest slope (ME.4) & distance between lake and parent glacier (ME.5)

Distance and slope between the lake and parent glacier determine the possibility of calving into the glacial lake (Wang et al., 2011). The most well-known example is the one from Lake Palcacocha in 1941, where a huge chunk of the adjacent glacier fell into the lake causing an outburst flood, severely damaging the city of Huaraz, and causing as many as 6000 deaths (Carey et al., 2012; Somos-Valenzuela et al., 2016). Previous studies have considered lakes within 500m of a glacier to be potential GLOF sources (e.g. Wang et al., 2011; Wang et al., 2015; Cook et al., 2016). Both lakes within 500m of a glacier could be impacted by ice and snow avalanches, which could also generate overtopping waves (Alean, 1985; Rickenmann, 1999, 2005). In addition, in the absence of detailed modelling of mass movement runout distances, we considered any proglacial lake within 500 m of a slope to be potentially dangerous, although we emphasise that the selection of these values is somewhat subjective. Overall, for both criteria (ME.4 & ME.5), we defined three risk classes as follows: 500 - 250m (low risk), 250 - 10m (medium risk), 10m - contact with lake (high risk).

Parent glacier snout steepness (ME.6)

For a parent glacier situated in proximity to a lake, a steep glacier snout can lead to enhanced levels of ice calving into the lake, which raises the risk of a GLOF (e.g. Grabs and Hanisch, 1993; Zapata, 2000; Wang et al., 2011). Following the classification of Wang et al. (2011) and Emmer et al. (2015) we derive three classes in parent glacier snout steepness: <15° (low risk), 15°-25° (medium risk) and >25° (high risk).

Flood wave size/runout

Travel distance of GLOF (SR.1)

One of the main parameters for GLOF risk assessment is to estimate whether the flood wave can reach downstream communities. For this estimation, a 'worst-case' approach is followed (Huggel et al. 2002). Studies have analysed the runout characteristics of debris flows from glacier/moraine-dammed lakes in the European Alps. It has been found that debris flows generally abate when they reach a downstream average slope of 11° and clean flows when they reach 3° (Haeberli, 1983; Huggel et al., 2002; Hegglin and Huggel, 2008). The average slope angle is thereby defined as the slope of a line between the start and end point of an outburst event. Therefore, in this study we used the thresholds of 3-7° (low risk), 7-11° (medium risk), >11° (high risk). We encourage the use of the Modified Single-Flow direction model (MSF) for experienced users (Huggel et al., 2003), and a new version of this has been developed by Rounce et al. (2016). Less experienced modellers may use Google Earth to find the average slope between the lake and potentially exposed communities or infrastructure.

Lake volume (SR.2)

Lake volume is regarded as a significant criterion since it determines the maximum amount of water that could be released downstream. Our original lake volume classification is derived from a global glacial lake dataset (Cook and Quincey, 2015) that includes water bodies ranging in size from supraglacial ponds (0.1×10^6 m^3) to very large lakes (770×10^6 m^3). Our thresholds were informed by plotting a frequency distribution of the dataset presented in Cook and Quincey (2015). Consequently, we derived three classes of risk: $<1 \times 10^6$ m^3 (low risk), 1×10^6 m^3 - 10×10^6 m^3 (medium risk) and 10×10^6 m^3 - 100×10^6 m^3 (high risk). Alternatively, one could also apply the Potential Flood Volume (PFV) method of Fujita et al. (2013) for moraine-dammed lakes where appropriate data are available.

Impact

Potential loss of human life (IM.1) & potential loss of infrastructure (IM.2)

GLOF risk implies that there must be downstream impacts such as potential loss of human lives and infrastructure. Glacier floods have directly caused at least: 7 deaths in Iceland, 393 deaths in the European Alps, 5745 deaths in South America and 6300 deaths in central Asia (Carrivick and Tweed, 2016). It is important to know the number of people under potential threat beforehand in order to suggest the appropriate measures. In order to rank the classes of risk by population affected we used thresholds set by international sources (Omelicheva, 2011; EM-DAT/Emergency Events Database) : <10 people (low risk), 10-1000 people (medium risk) and >1000 people (high risk). As for infrastructure, we graded the severity from high, where a hydraulic dam, mining camp or a historic/heritage site is under threat, to low, where damage to agricultural fields or dirt roads may indirectly affect the local population. It is important to use the best population data available. If no data exist, we suggest to estimate population using a combination of Google Earth (to identify number of households) and the United Nations Statistics Division (UNSD; https://unstats.un.org/unsd/demographic/) data for people per household in the country of interest.

Additional references:

Alean J., 1985. Ice avalanches: some empirical information about their formation and reach. J Glaciol. 31(109), 324–33.

Emmer, A., Merkl, S., Mergili, M., 2015. Spatiotemporal patterns of high-mountain lakes and related hazards in western Austria. Geomorphology 246, 602–616. doi:10.1016/j.geomorph.2015.06.032

Emmer, A., Vilímek, V., Huggel, C., Klimeš, J., Schaub, Y., 2016b. Limits and challenges to compiling and developing a database of glacial lake outburst floods. Landslides 1–6. doi:10.1007/s10346-016-0686-6Figueira, J., Greco, S., Roy, B., Słowiński, R., 2013. An Overview of ELECTRE Methods and their Recent Extensions. J. Multi-Criteria Decis. Anal. 20, 61–85. doi:10.1002/mcda.1482

Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps, Ann. Glaciol., 4, 85–90.

Omelicheva, M.Y., 2011. Natural Disasters: Triggers of Political Instability? Int. Interact. 37, 441–465. doi:10.1080/03050629.2011.622653

The Society for Risk analysis (SRA) glossary, June 22, 2015
(http://www.sra.org/sites/default/files/pdf/SRA-glossary-approved22june2015-x.pdf)

Wang, X., Liu, S., Ding, Y., Guo, W., Jiang, Z., Lin, J., Han, Y., 2012. An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data. Nat. Hazards Earth Syst. Sci. 12, 3109–3122. doi:10.5194/nhess-12-3109-2012

Wang, X., Ding, Y., Liu, S., Jiang, L., Wu, K., Jiang, Z., Guo, W., 2013. Changes of glacial lakes and implications in Tian Shan, central Asia, based on remote sensing data from 1990 to 2010. Environ. Res. Lett. 8, 44052. doi:10.1088/1748-9326/8/4/04405

Appendix 4.2. Lake evaluation

Table 1 - Quantitative criteria evaluation for the global lake dataset. For the criteria ME.1, ME.6 and IM.1 it is impossible to give an exact value due to the resolution of Google Earth imagery, or due to missing information. For the criterion ME.3, Google Earth does not let the user to identify the exact value of slopes >45 degrees.

Dangerous lakes - literature	**Coordinates in UTM**			**TR.1**	**TR.2**	**TR.3**	**ME.1**	**ME.2**	**ME.3**	**ME.4**	**ME.5**	**ME.6**	**SR.1**	**SR.2**	**IM.1**	**IM.2**
Maud lake	59 G	459482	5185818	3.4	13	43	15-5	moraine	30	260	470	<15	3	78	<10	roads, fields, individual buildings
Godley lake	59 G	461555	5188206	3.4	13	43	>15	moraine	35	30	contact	<15	3	102	<10	roads, fields, individual buildings
Chholamo	45 R	672675	3099360	2.1	116	61	15-5	moraine	15	400	470	<15	3	41	<10	roads, fields, individual buildings
Lake 0071	45 R	676212	3084379	2.1	116	61	15-5	moraine	20	290	340	<15	7	1.71	10-1000	densely populated area
Hanpi k'ocha	18 L	743739	8534059	2.5	74	12	15-5	moraine	>45	contact	230	>25	7	1.9	>1000	densely populated area
Gopang Gath	43 S	708269	3601049	2.5	39	70	15-5	moraine	35	330	contact	15-25	6	27	10-1000	densely populated area
Spong Tongpo	43 S	658545	3769166	1.9	35	90	<5	moraine	30	190	contact	15-25	4	3.1	10-1000	densely populated area
Schako Tsho	45 R	658915	3095511	2	112	60	15-5	moraine	>45	65	contact	>25	6	18.14	10-1000	densely populated area
Imja Tsho	45 R	492610	3085944	4.9	121	57	<5	moraine	>45	230	contact	<15	6	65	>1000	densely populated area
Tsho Rolpa	45 R	448360	3082066	5.2	116	54	15-5	moraine	>45	contact	contact	>25	7	78	>1000	densely populated area
Thulagi Tsho	45 R	253755	3153985	4.2	101	44	<5	moraine	>45	contact	contact	<15	12	35	>1000	hydopower, buildings, roads
Dig Tsho	45 R	459210	3083375	5.2	117	55	<5	moraine	>45	contact	contact	>25	6	10.7	>1000	densely populated area
Lower Barung Tsho	45 R	509355	3074824	5	109	53	<5	moraine	>45	contact	contact	<15	7	83	>1000	hydopower, buildings, roads
Ludming Tsho	45 R	461884	3072885	5.2	112	52	<5	moraine	>45	contact	contact	15-25	3	50	10-1000	densely populated area
Chamlang South Tsho	45 R	495956	3069986	5.1	117	55	>15	moraine	>45	contact	contact	>25	7	32	10-1000	densely populated area
Chamlang North Tsho	45 R	495685	3073227	5.1	117	55	15-5	moraine	>45	contact	contact	>25	7	32	10-1000	densely populated area
Selected GLOF events	**Coordinates in UTM**			**TR.1**	**TR.2**	**TR.3**	**ME.1**	**ME.2**	**ME.3**	**ME.4**	**ME.5**	**ME.6**	**SR.1**	**SR.2**	**IM.1**	**IM.2**
Flatbreen lake - 2004	32 V	382775	6817696	0.7	32	5	15-5	moraine	35	400	contact	15-25	17	0.1	<10	roads, fields, individual buildings
Passu lake - 2007	43 S	489281	4034749	1.9	56	97	15-5	moraine	>45	50	contact	>25	6	1.8	>1000	densely populated area
Keara lake - 2009	19 L	481958	8377253	2.1	70	13	15-5	ice	25	contact	contact	>25	8	0.2	10-1000	densely populated area
513 lake - 2010	18 L	219809	8980678	3.6	73	7	15-5	moraine/bedrock	35	contact	contact	>25	8	4	10-1000	densely populated area
Halji lake - 2011	44 R	545635	3348799	5.8	77	57	15-5	ice	25	470	contact	>25	12	1	10-1000	historic temple, buildings, roads
Chorabari lake - 2013	44 R	314434	3403219	3.8	69	60	<5	moraine	30	contact	340	<15	17	0.4	>1000	historic temple, buildings, roads

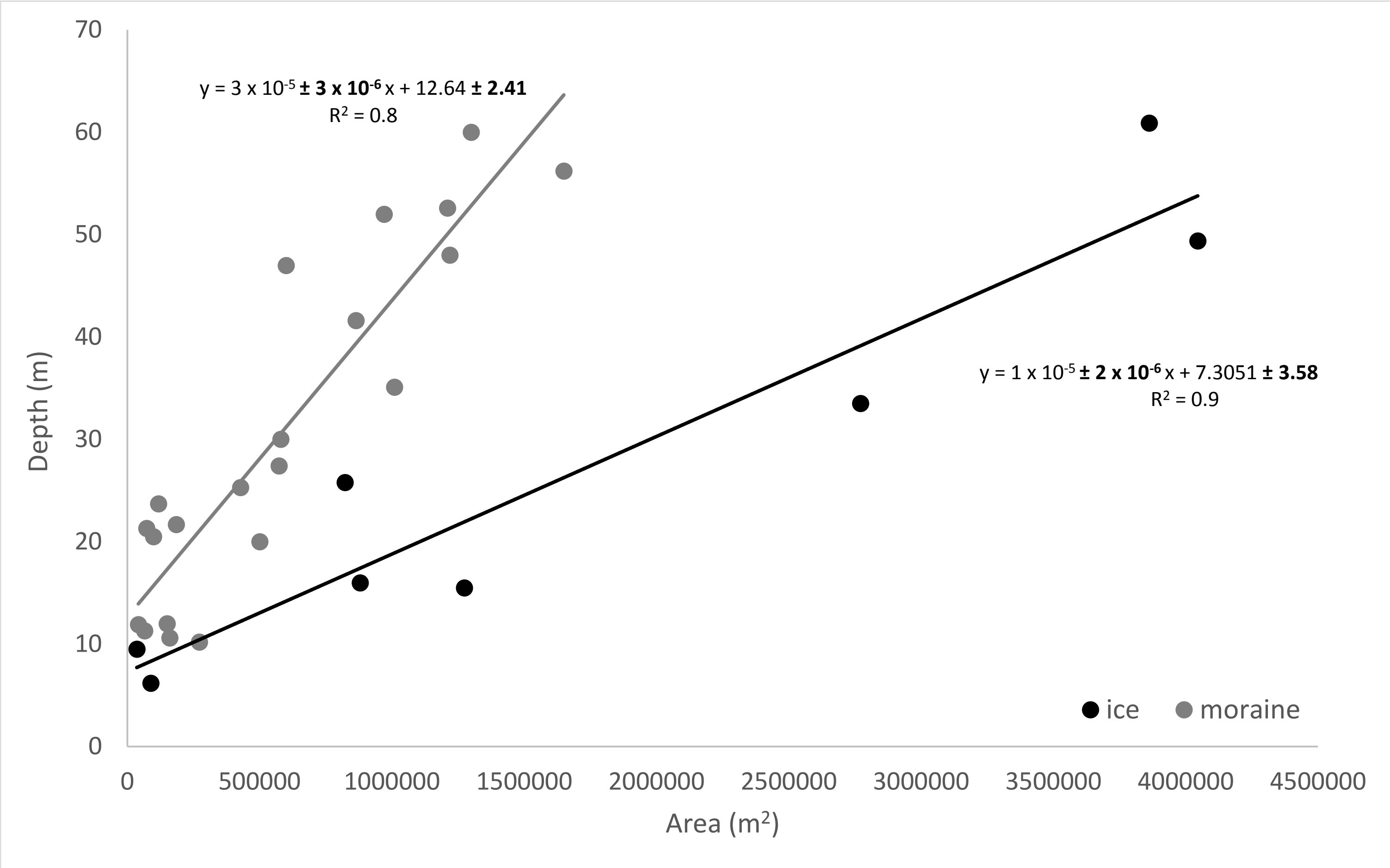
Table 2 - Qualitative criteria evaluation for the global lake dataset. Low risk = 1, Medium risk = 2, High risk = 3.

Dangerous lakes - literature	**Coordinates in UTM**			**TR.1**	**TR.2**	**TR.3**	**ME.1**	**ME.2**	**ME.3**	**ME.4**	**ME.5**	**ME.6**	**SR.1**	**SR.2**	**IM.1**	**IM.2**
Maud lake	59 G	459482	5185818	2	1	1	2	2	2	1	1	1	1	3	1	1
Godley lake	59 G	461555	5188206	2	1	1	1	2	2	2	3	1	1	3	1	1
Chholamo	45 R	672675	3099360	2	3	2	2	2	1	1	1	1	1	3	1	1
Lake 0071	45 R	676212	3084379	2	3	2	2	2	1	1	1	1	1	2	2	2
Hanpi k'ocha	18 L	743739	8534059	2	2	1	2	2	3	3	2	3	1	2	3	2
Gopang Gath	43 S	708269	3601049	2	1	2	2	2	2	2	3	2	1	3	2	2
Spong Tongpo	43 S	658545	3769166	2	1	2	3	2	2	2	3	2	1	2	2	2
Schako Tsho	45 R	658915	3095511	2	3	2	2	2	3	2	3	3	1	3	2	2
Imja Tsho	45 R	492610	3085944	3	3	2	3	2	3	2	3	1	1	3	3	2
Tsho Rolpa	45 R	448360	3082066	3	3	2	2	2	3	3	3	3	1	3	3	2
Thulagi Tsho	45 R	253755	3153985	3	3	1	3	2	3	3	3	1	3	3	3	3
Dig Tsho	45 R	459210	3083375	3	3	2	3	2	3	3	3	3	1	3	3	2
Lower Barung Tsho	45 R	509355	3074824	3	3	2	3	2	3	3	3	1	1	3	3	3
Ludming Tsho	45 R	461884	3072885	3	3	2	3	2	3	3	3	2	1	3	2	2
Chamlang South Tsho	45 R	495956	3069986	3	3	2	1	2	3	3	3	3	1	3	2	2
Chamlang North Tsho	45 R	495685	3073227	3	3	2	2	2	3	3	3	3	1	3	2	2
Selected GLOF events	**Coordinates in UTM**			**TR.1**	**TR.2**	**TR.3**	**ME.1**	**ME.2**	**ME.3**	**ME.4**	**ME.5**	**ME.6**	**SR.1**	**SR.2**	**IM.1**	**IM.2**
Flatbreen lake - 2004	32 V	382775	6817696	2	1	2	2	2	2	1	3	2	3	1	1	1
Passu lake - 2007	43 S	489281	4034749	2	2	2	2	2	3	2	3	3	1	2	3	2
Keara lake - 2009	19 L	481958	8377253	2	2	1	2	3	1	3	3	3	2	1	2	2
513 lake - 2010	18 L	219809	8980678	2	2	1	2	2	2	3	3	3	2	2	2	2
Halji lake - 2011	44 R	545635	3348799	3	2	2	2	3	1	1	3	3	3	2	2	3
Chorabari lake - 2013	44 R	314434	3403219	2	2	2	3	2	2	3	1	1	3	1	3	3

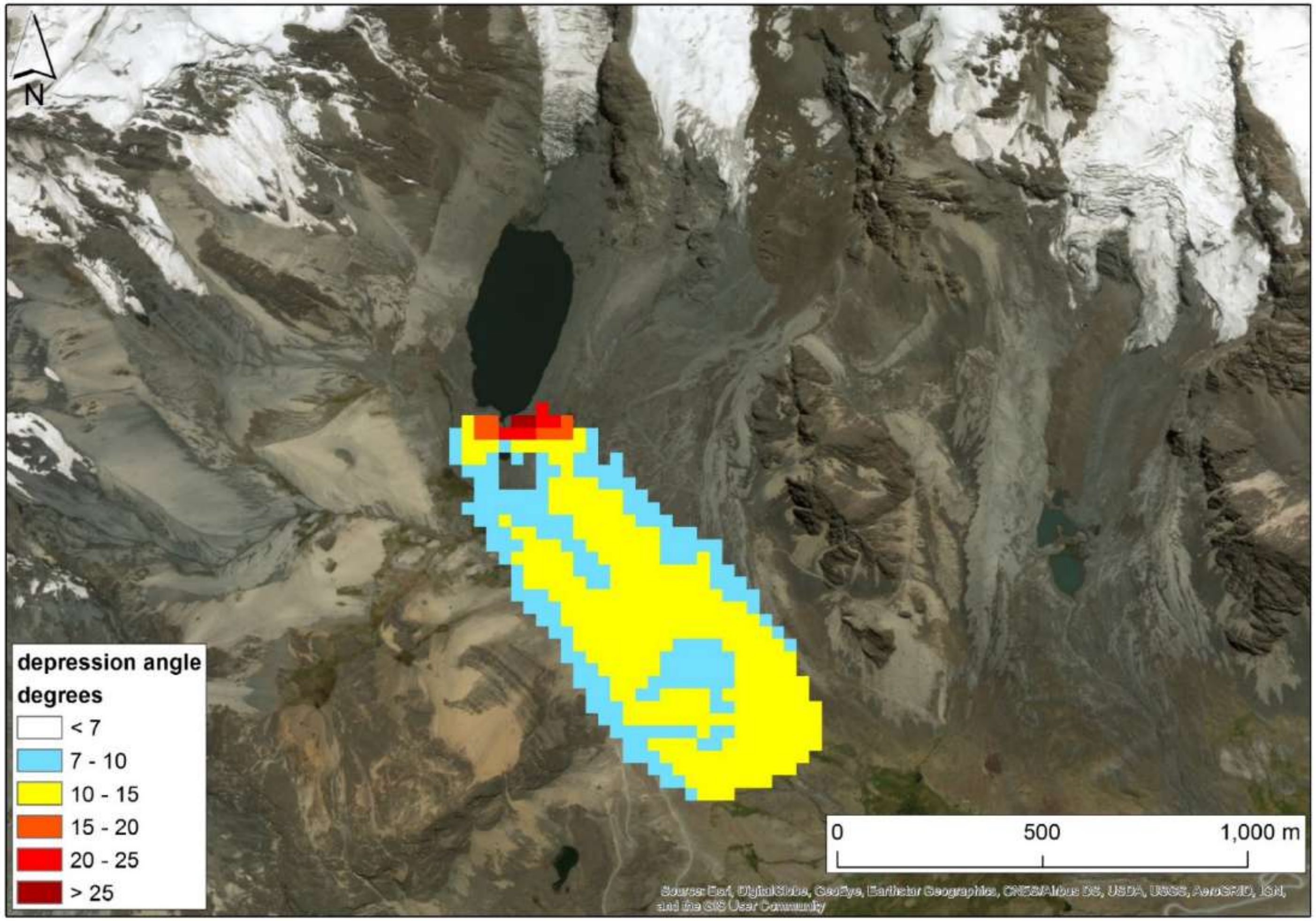
Table 3 - Qualitative criteria evaluation for the Bolivian lake dataset. Low risk = 1, Medium risk = 2, High risk = 3.

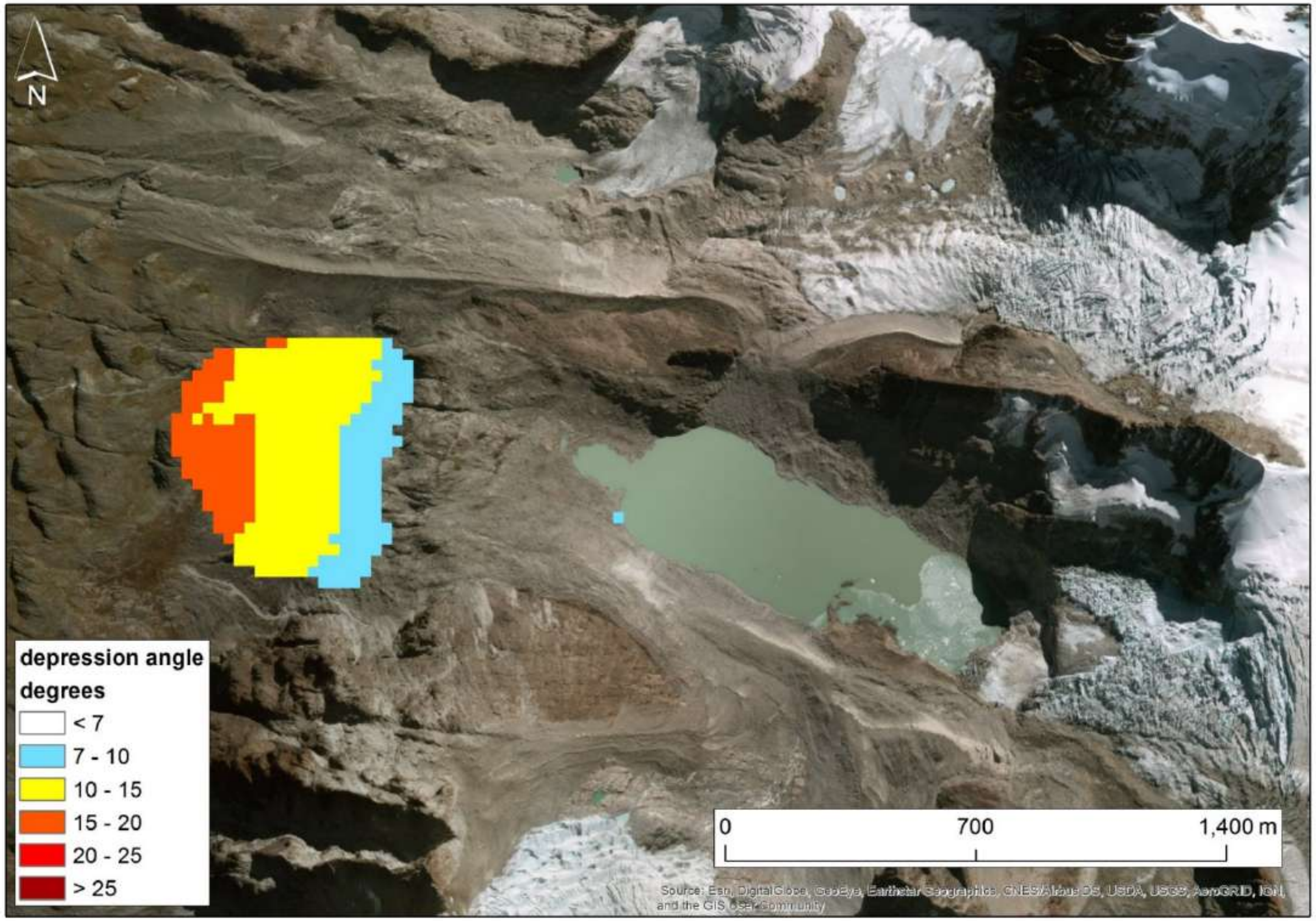
Lakes	Coordinates in UTM			TR.1	TR.2	TR.3	ME.1	ME.2	ME.3	ME.4	ME.5	ME.6	SR.1	SR.2	IM.1	IM.2
Apolobamba - Puina	19 L	476504	8384832	2	2	1	2	2	1	2	3	2	2	1	1	1
Apolobamba - Pelechuco	19 L	481205	8365591	2	2	1	2	2	3	3	2	2	2	2	3	2
Apolobamba - Hilo Hilo 1	19 L	492850	8354529	2	2	1	3	1	1	2	2	1	2	2	1	1
Apolobamba - Hilo Hilo 2	19 L	487996	8349572	2	2	1	3	1	1	1	2	2	2	1	1	1
Apolobamba - Hilo Hilo 3	19 L	487666	8349316	2	2	1	3	1	2	2	2	1	2	1	1	1
Apolobamba - Puyo Puyo	19 L	486275	8351196	2	2	1	2	1	1	1	3	2	1	1	1	1
Apolobamba - Taypi Cayuma 1	19 L	491182	8343142	2	2	1	2	1	2	2	2	1	1	1	1	1
Apolobamba - Taypi Cayuma 2	19 L	492072	8340807	2	2	1	3	2	3	1	1	1	1	1	1	1
Apolobamba - Cholina Cholina 1	19 L	497085	8337363	2	2	1	2	2	3	2	1	1	2	1	1	1
Apolobamba - Cholina Cholina 2	19 L	498284	8335884	2	2	1	3	2	1	1	1	3	1	1	1	1
Real - Laguna Glaciar	19 L	547085	8249728	2	2	1	3	1	2	2	3	2	2	2	3	2
Real - Cocoyo 1	19 L	556846	8251418	2	2	1	3	1	1	1	2	1	3	1	1	1
Real - Cocoyo 2	19 L	559120	8249880	2	2	1	2	1	1	1	2	1	3	1	1	1
Real - Cocoyo 3	19 L	560553	8247486	2	2	1	3	1	2	2	2	1	3	2	1	1
Real - Rinconada 1	19 L	552071	8244232	2	2	1	2	2	2	2	3	3	1	1	1	1
Real - Rinconada 2	19 L	550069	8242190	2	2	1	2	2	2	2	3	3	1	1	1	1
Real - Laguna Wara Warani	19 K	567694	8222503	2	2	1	2	1	2	2	2	1	1	2	1	1
Real - Umapalca	19 K	584186	8220965	2	2	1	3	1	2	3	2	1	2	2	1	1
Real - Condoriri	19 K	578927	8210860	2	2	1	2	1	1	1	1	2	1	2	1	1
Real - Comunidad Pantini	19 K	612872	8182149	2	2	1	3	1	2	2	1	1	1	1	1	1
Mururata - Laguna Arkhata	19 K	624521	8172040	2	2	1	2	1	3	2	3	2	3	3	3	2
Tres Cruces - North	19 K	670245	8126070	2	2	1	3	2	2	1	2	1	1	1	1	1
Tres Cruces - Mining camp west	19 K	674446	8120893	2	2	1	2	1	2	2	1	1	3	1	2	3
Tres Cruzes - Mining camp east	19 K	678278	8121207	2	2	1	3	2	1	1	1	1	2	1	2	3
Tres Cruces - Laguna Huallatani	19 K	675910	8118767	2	2	1	2	1	1	1	1	1	2	3	3	2

Appendix 5.1. **Ice-dam and moraine-dam lake area-depth relationships with constant errors (from the lake dataset provided by Cook and Quincey, 2015).**

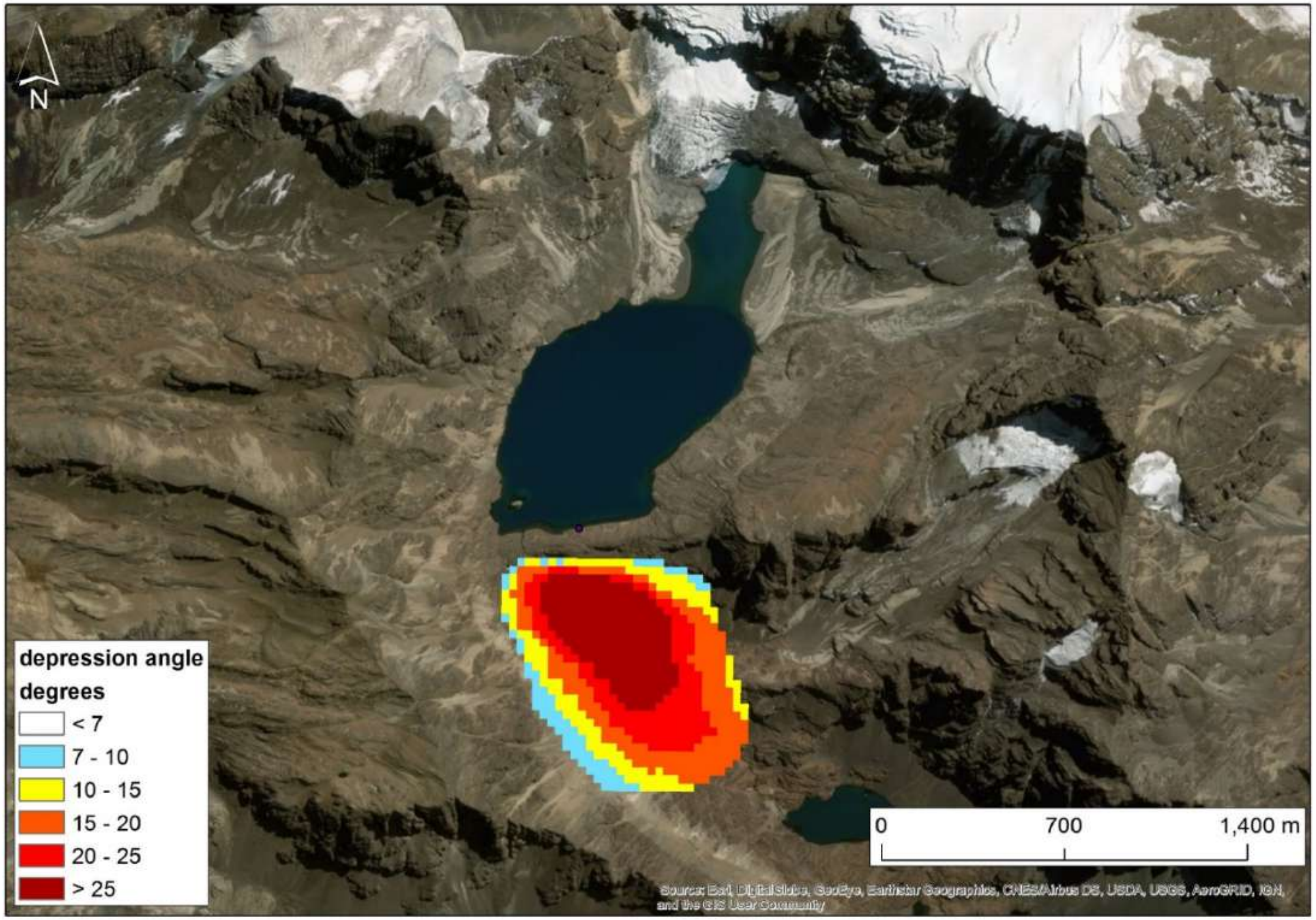


Appendix 5.2. Estimated depression angles for each lake according to the method suggested by Fujita et al. (2013). Top, Pelechuco Lake. Middle, Laguna Glaciar. Bottom, Laguna Arkhata.





N
depression angle
degrees
< 7
7 - 10
10 - 15
15 - 20
20 - 25
> 25
0
700
1,400 m
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community


N
depression angle
degrees
< 7
7 - 10
10 - 15
15 - 20
20 - 25
> 25
0
700
1,400 m
Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Appendix 6.1. PhD results workshop

The workshop focused on the main results of this PhD concerning "Glacier change and Glacial Lake Outburst Floods in the Bolivian Andes". It took place in La Casona Hotel-Boutique in La Paz, Bolivia on the 06 of July 2018 from 9am to 12pm.

List of Participants:

Ioannis Kougkoulos	Manchester Metropolitan University
Elias Symeonakis	Manchester Metropolitan University
Paula Pacheco	Agua Sustentable
Fanny Zeballos	Agua Sustentable
Sébastien Hardy	Institut de recherche pour le développement (IRD)
Freddy Soria Cespedes	Universidad Católica Boliviana San Pablo (UCB)
Fabrizio Uscamayta	Universidad Mayor de San Andrés (UMSA)
Martin Apaza Ticona	Identidad Madidi
Maria Copa Alvaro	Colección Boliviana de Fauna
Yaruska Castellón	Servicio Nacional de Meteorología e Hidrología de Bolivia (SENAMHI)

Program:

9:00 – 9:15	Presentation of PhD results
9:15 – 10:30	Questions and discussion of the results
10:30 – 10:45	Coffee break
10:45 – 12:00	Potential collaborations, action points etc.

Top: Ioannis Kougkoulos presenting two and a half years of work on modelling GLOFs in Bolivia. Bottom: All participants gathered after the workshop for a photo.

Agua Sustentable

Manchester Metropolitan University

La Paz, 11 de junio de 2018

Señor

Lic Javier Quiroga

Presente

Ref.: INVITACIÓN TALLER "RETROCESO DE LOS GLACIARES Y DESASTRES NATURALES EN BOLIVIA"

De nuestra consideración:

A tiempo de saludarle fraternal y respetuosamente, hacemos propicia la oportunidad para invitarle al taller titulado **"Retroceso de los Glaciares y Desastres Naturales en Bolivia"** con el fin de abordar los distintos aspectos relacionados con el retroceso de los glaciares y recursos del agua, como también desenvolver un análisis en conjunto sobre la gestión de desastres naturales en Bolivia.

Dicho taller se llevara a cabo en **La Casona Hotel Boutique** – La Paz, el día 6 de julio del presente año a partir de hrs. 09:00 a.m.

Así mismo puede confirmar su participación escribiéndonos al e-mail *ioannis.kougkoulos@gmail.com* o comunicándose al *Tel: +591 (2)* 2112682. ***Seguros de contar con su participación, nos despedimos de usted, deseándole muchos éxitos en la presente gestión.***

Official letter to workshop participants from MMU and Agua Sustentable.